RESEARCH AND MODEL STUDIES ON RANGE ACTION IN TABLE BAY HARBOUR, CAPE TOWN.

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RESEARCH AND MODEL STUDIES

ON

RANGE - ACTION

IN

TABLE BAY HARBOUR, CAPE TOWN

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" ....if many useful discoveries have been made by accident when men were not seeking for them but were busy about other things, no man can doubt but that when they apply themselves to seek and make this their business, and that, too, by method and in order and not by desultory impulses, they will discover far more".

—— Francis Bacon.
Novum Organum, (1620)

PREFACE

The demand for a model study of the Range problem in Table Bay Harbour was referred late in 1941 to the Research Section of the Chief Civil Engineer's Department of the South African Railways and Harbours, the Research Engineer being requested to undertake an investigation. The Research Engineer of the time, Dr. C. V. von Abo, and the author commenced the task in January, 1942, by visiting Cape Town to sample nautical and technical opinion and study conditions, provisionally, on site.

In the succeeding months the work of analysing such permanent harbour records as existed, of devising and designing instruments for measuring wave effects in the harbour, and of planning for an engineering model, devolved almost entirely upon the author, as the Research Engineer was called upon to act in another post for a period of several months.

This necessarily imposed a heavy responsibility on the author, at a time when he had only limited experience of model experimental-technique, and no special knowledge of the principles of similitude and of hydrodynamics. The problem, too, was one of national importance and pressing urgency. To make matters more onerous, the author had to contend with a shortage of technical assistance and severe wartime restrictions on materials, many commodities being unobtainable and suitable instruments for refined measurements for the research being simply unprocurable, either locally or overseas.

Even in the face of these difficulties it was possible to report fair progress by the end of July, 1942, when the Research Engineer resumed duty, and thereafter Dr. von Abo paid the author the considerable compliment of giving him almost a free hand in the conduct of the research.

Special instruments for recording sea-oscillations, hereafter to be referred to as 'Seichometers', were designed and fabricated before the end of the winter of 1942, but an unfortunate mishap which delayed the permanent installations at the harbour, prevented their being brought into operation in time to measure Range effects that winter. Nevertheless, the basic nature of the Range phenomenon had already been recognized, and it was possible to proceed at once to the design of the harbour model.

In January, 1943, the author was called down to Cape Town to report to the Minister and the General Manager of Railways and Harbours*. As a result thereof he was transferred to Cape Town at the end of April, 1943, to continue the research and model development on site.

It is convenient here to give a brief exposition of how the research unfolded from this point, since, in the work hereunder, we shall depart radically from the order in which particular phases of investigation were pursued or conclusions reached.

The collection of data from actual observation and measurement was begun at once upon the author's assumption of duty at Cape Town, and simultaneously, designs were pushed ahead for the wave-paddle mechanisms and driving machinery for the model, as well as for the model itself and its many details.

Construction of a laboratory to house the model and research staff within the harbour area was undertaken independently by the Harbour Engineer†, and was largely complete by the end of 1943.

Until July, 1943, the author could command the services of only one draughtsman, but from then until April, 1945, the position was somewhat relieved by the appointment

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* Respectively, the Hon F. Claude Sturrock and Brigadier C. M. Hoffe. M.Inst.T.

† Mr. G. Lankaster, B.Sc., A.M.I.C.E.

of a second assistant. Nevertheless, the volume of work remained at all times beyond the capacity of the available research staff, and this fact requires to be borne in mind in respect of the overall length of time taken for the consummation of the research.

By November, 1943, the design of the model and all appurtenances, exclusive, however, of measuring instruments, was complete, and construction of the model was begun.

In the meanwhile records of sea-oscillations obtained from the seichometers had been accumulating and required to be analysed. The problem of detecting individual harmonic components in the complex curves had to be grappled, for which it was necessary to make a close study of harmonic analysis. While these studies proceeded, graphical methods were applied to examine wave expansion in Table Bay as a check on aerial photographs of swell movements, and also to determine the directions and phase-difference settings for the two wave-paddles in the model. First measurements were also made to correlate ship-movements and Range-action (July, 1943).

The question of automatically recording water movements in the model for comparison with those in Nature was also a matter of concern about this time. The problem had already been considered tentatively in 1942 when it was realised that any of the standard instruments for the purpose would be utterly unprocurable. When model designs were finished it was possible to continue developmental work on a suitable apparatus. By April, 1944, the detailed design of an autographic instrument, which we have called a '<u>Kymatograph</u>' or wave-recorder, was completed and its manufacture put in hand.

During the period that the model was under construction, (November, 1943, to May, 1944) a great volume of work in other directions was accomplished. Individual seichograms for different parts of the harbour were retraced and synchronised; mathematical harmonic analysis of typical seichograms was undertaken; graphical processes were extended to the investigation of wave reflections and the positions of nodal lines of oscillations near the harbour; and a study was commenced of the relationships between meteorological disturbances and Range-action.

The Kymatograph was received in August, 1944, but as might be expected of a first edition of a new device, additional parts and modifications were found necessary, all of which effectively delayed use of the apparatus as a reliable working instrument until January, 1945. At the same time various 'teething' troubles were experienced with the wave-paddle machinery, in which it was necessary to instal auxiliary shafting, pulleys and gears to increase the sensitivity of speed-control.

In the interim period while these adjustments were being made the work of accumulating and analysing seichograms proceeded steadily. Further measurements of ship-movements in relation to Range-action were secured, and graphical methods were used to study the expansion of waves within the harbour basins.

About this time, the discovery was made that barometric fluctuations were linked with sea-oscillations in the bay. This led to the improvisation of a microbarograph, with which minute variations of pressure were correlated with occurrences of Range-action.

Because of pending adjustments to the paddle machinery and the Kymatograph, the model could not be used in 1944 for experiments directed towards solving the Range problem. Nevertheless, it was possible in a qualitative way to demonstrate the success of the model in reproducing the phenomenon, and such demonstrations were frequently made from April, 1944, onwards. But they appear to have created the unfortunate impression among returning visitors, that the model, although ostensibly complete, was not being used toward the practical result of obtaining a solution.

The model was only in satisfactory working order by the beginning of February, 1945, but the problem of how to adjust and operate the paddles remained to be resolved. Throughout February, March and April, 1945, experiments were made to determine paddle settings and to check the general reliability of the model. The latter tests involved the travelling times of waves and the form of wave expansions.

Just at this time, unfortunately, the productive capacity of the research was curtailed by the resignation from the Service of one of the author's two assistants. Despite repeated appeals for a replacement, no further assistance was forthcoming, and the research from then on was inevitably protracted.

From May to October, 1945, the author wrestled with the problem of arranging that the two paddles impart wave-energy to the model in the proportions that wave-energy enters the two channels of Table Bay. Ancillary experiments to determine the dispersion of wave-energy with wave-expansion and propagation had to be made and the results analysed, before this issue could be decided. Before correlating the paddles it was necessary to know what energy each transmitted at a given setting, and here, after electrical and manual methods of measurement proved unavailing, it was found necessary to design special dynamometers.

In this period also, the authorcommenced the analysis of factors affecting the ranging action of ships, and this question assumed increasing importance as theory unfolded and additional measurements on ship motions came to hand.

The original urgency for the solution of the Range problem had abated considerably by this time, with the re-opening of the Mediterranian shipping routes and the reduction of shipping volume in Cape waters, as also with advent of more clement weather: for it was a noticeable fact that Range had diminished very markedly in severity since 1942. There was nevertheless no relaxation in the steady pursuit of a solution to the problem. Premature experiments on specific ways of solving the problem could have been undertaken as from May, 1945, by operating the wave-paddles haphazardly, but as the results of such experiments would have been, in general, unreliable, the author preferred to proceed along thorough lines by putting the model in sound working order first, before embarking on the final experiments.

At this juncture, (November, 1945), the 'Aquitania' arrived in Table Bay and was withheld from docking, allegedly because of the dangers of Range-action. This unfortunate incident raised such a public outcry against the disabilities from which the port suffered through notoriety from the Range, that the matter became again one of the highest priority.

Regrettably the opinion seems to have been formed that the research was not proceeding with the requisite vigour. It was no doubt hard for those who were unfamiliar with the problems of constructing a model and conducting the research, or with the staff conditions under which the research was being made, to comprehend why it had not been possible to reach a definite conclusion long before this. In deference to popular demand preliminary experiments on the model were conducted throughout December, 1945, and January, 1946, all of which had, however, to be repeated at a later date.

From February until the end of November, 1946, after it had been shown that there was no easy shortcut route to a solution, the author was able to continue the research very much as originally planned. During this period the main experiments described in these pages were conducted, and the study of ship motions was advanced to a stage of usefulness which not only enabled the most dangerous Range oscillations to be ascertained, but also the required efficiency of any proposed solution of the problem.

The transfer of the author back to Johannesburg in December, 1946, marked the effective termination of the research, although, in the interval since, further data have been accumulated as matter of routine.

The writing of this work has been undertaken in the author's spare time since that date, and many aspects of the problem which fell outside the terms of reference of the official research, particularly those relating to the nature and origins of the Range phenomenon, have been privately pursued and extended. Sufficient was gleaned in this process to make it the semblance of a duty to the author that the findings should be made available in some form, but as the magnitude of the task unfolded, he perceived that a thesis presented the only really satisfactory medium for recording so voluminous an undertaking.

This manuscript differs vastly in form and context from the many reports that were submitted in connection with the research. It embodies for the most part only the ideas which the author originated and the work which he personally executed or directed. Full acknowledgement by footnotes in the text is made of sources of information, suggestions and conclusions which have been utilised as having relevant bearing on the development of the research.

The investigation was made under the general direction of the former Chief Civil Engineer, Mr. J. S. de V. von Willich, B.Sc., A.M.I.C.E., M.(S.A.)I.C.E., to whom acknowledgement is due for many helpful suggestions, and of the Research Engineer, Dr. C. V. von Abo, M.A., Ph.D., until the latter's retirement from the Service in September, 1945, whose interest and encouragement were always stimulating.

Special mention should be made of the sterling services rendered by Mr. W. C. Q. Joosting, Dip. Ing. (Zurich), A.M.(S.A.)I.C.E., draughtsman and later as assistant engineer, and by Mr. R. de Boor, A.M.(S.A.)C.I., draughtsman, both of whom laboured through the great bulk of the intricate drawing and calculation work. Of the excellence and accuracy of Mr. Joosting's work the author would add a special word of commendation. Invaluable help was also rendered by Mr. J. Cowan, clerk, in the final stages of the research in collecting statistical data and in so successfully assuming the functions of auxiliary draughtsman.

Acknowledgement should also be made to Colonel D. E. Paterson, B.Sc., M.I.C.E., formerly Assistant Chief Civil Engineer (Harbours), to Mr. G. Lankaster, B.Sc., A.M.I.C.E., M.(A.S.)I.C.E., former Harbour Engineer, Cape Town, and his staff, and to Captains J. Short and C. G. White, successively Port Captain's at Cape Town, and their staff, whose unfailing interest and sympathetic assistance were so generously accorded throughout the undertaking.

For the ultimate success of the model, its machinery and instruments, credit is due to many others, too numerous to mention, who took part in their construction and fabrication. Finally the author is indebted to the Management of the South African Railways and Harbours for permission to use the material accumulated during the researches for the compilation of this work and its presentation as a thesis.

Johannesburg

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INTRODUCTION.

> " Naturam expelles furca, tamen usque recurret,"
>
> — Horace,
> Epistles, Book I, (c.10 BC)

Standing on a promontory watching the surf lashing a rock-bound coast or breaking on a sandy shore, how many of us are prompted to wonder why and how: or standing on the bank of a placid pool waiting for the sound and ripple-rings that will mark the grave of a falling stone, how many of us are tempted to enquire beyond the mere perceptions of our senses? At such times transient queries may doubtless rush to our minds, but are usually dispelled for want of explanation. Yet there have always been among men a more discerning few, who, having seen and wondered, have felt an impulsion to know more. To the enduring patience of these few, to their powers of observation and rich endowments in mathematical skill, the world owes the sciences of oceanography and hydrodynamics - sciences which constitute the optics whereby we less perceptive mortals may look upon the workings of Nature.

But these optics are never perfect, and the finer the focus and the greater their discerning power, the vaster is found the Unknown which Nature veils from our view. It is perhaps not so often these days that men peer into this obscurity from mere personal desire to gratify their scientific curiosity; more often now they are appointed to the tasks of probing this Unknown as a safeguard against the recoils inflicted by Nature, which history has shown are the reward for temerity in blunt incursions that meddle with the play of natural forces.

For it is an oft-repeated story that civilization, in its headstrong course, has continually blundered against the unknown vagaries of the sea. Harbours have been built, sea-walls erected, reclamations made, often with scant regard for the fact that these have been encroachments upon the fringe of the Unknown. Haste in pursuit of wealth has been costly, and many are the cases on record of Nature reasserting herself to wreck man's flimsy structures, undermine his sea-defences, erode his land and invade his shore. In spite of these reverses mankind has been slow to learn that it pays to be wary, and that in dealing with a vicissitudinous sea it may be worth the while to view the scene beforehand through the optics of the sciences.

The harbour at Cape Town is only another example of contact between Man and Nature, in which Nature has from time to time issued sharp reminders that his actions have been perhaps/rather hasty. This does not mean that the engineers and promoters who so painstakingly studied the conditions and built the harbour failed in their allotted tasks. They merely suffered from the disadvantage that they lived in times when the rebuffs of Nature, though many and severe, had not yet brought the enlightenment that now cautions us to feel our way through the medium of research. The engineers had neither the time nor the opportunity to explore unknown factors at which they could only guess. Had the advantages of model research been more persuasive and earlier realized, the harbour might have been constructed differently - the breakwater in another position, the basins of different shapes and dimensions, the reclamations in new locations, and the erosion that now stalks the Milnerton shore of Table Bay, and the Range-action that has since reared itself in troublesome proportions within the docks, might not have been problems as they are today.

The present work, which seeks to place on record the findings of a survey, made through the optics of the sciences, of some of that Unknown to which we have alluded, treats in particular of the phenomenon of Range-action.[*] For Range has been of the Unknown to the extent that it has never locally been fully understood: and the principal reason for this is that in all but its effects it remains something invisible, intangible and mysterious, an object of speculation and misconception.

Range has been variously referred to as scend, undulation, run, surge, swell, ground-swell, surf, or merely wave-action, but all these terms have been so loosely applied, or are so ill-defined, that they merely confuse recognition of the phenomenon. Range in point of fact connotes something of all these actions without being adequately described by any one, and at this stage it is best defined by what it does, rather than by what it is.

Range usually manifests itself in visible form by the reversible currents it induces through the entrances of the harbour basins, and in invisible form by the motion it communicates to ships moored at the quays within the docks. During occurrences of Range action ships in various parts of the harbour tend to move uneasily in their berths with fore-and-aft and off-and-on motions which at times impose serious strains on the mooring ropes and heavy pressures on the floating fenders. The action is undesirable at all times, for if ropes are slack and Range action severe, whole

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[*] At Cape Town the phenomenon was, formerly, commonly known as 'Run'. It would appear that the term 'Range', the accepted technical terminology adopted by the engineering profession (cf. Proc. Inst. C.E., v. 209, 1920, [1], pp. 189-250) was introduced locally first by Mr. George Stewart when giving evidence before the Table Bay Harbour Improvements Committee in September, 1921. (Mr. Stewart had attended the Institution of Civil Engineers' meeting in London in 1920).

moorings can be torn asunder and permanent damage caused to ships and harbour installations alike. There have been occasions, too, when floating fenders have been crushed and ships' shell-plating dented at the waterline by the tremendous impact pressures developed.

These conditions often, but not always, accompany severe winter storms, but they occur sometimes also in the summer months and even during quiescent spells in winter. Their relative infrequency has been perhaps the most potent reason why they have been tolerated so long, for, as we shall see, the conditions were present even when the harbour was in embryo. They would no doubt have continued to be regarded as something ephemeral had not a crisis been precipitated by the concurrence of exceptionally severe Range action with unusually large numbers of ships in Table Bay during a most critical stage of the recent World War. For in the period 1940 to 1942, when the Mediterranean shipping lanes were closed, large convoys of ships of many sizes were using Cape Town as a port of call, and by chance the winters of those years produced the most severe occurrences of Range action that have been known before or since. Extraordinary scenes prevailed, for at one time (June 19th, 1942), no less than 83 mooring ropes on different ships parted and 10 sets of floating fenders were smashed. On another occasion (May 28th, 1940), the 'Mauretania' of 42,000 tons, displacement tonnage, alone broke 44 ropes consisting of 18-inch (circumference) coir strops and 4½-inch (circumference) steel hawsers, while other ships accounted for yet another 16 fractured ropes. Some ships inevitably sustained damage, and as damage from such causes, when shipping was the very life blood of the Western Allies, was nothing less than a minor disaster, it was natural that the incidents should have been viewed with the gravest concern.

It is as well to appreciate that at this time the construction of the new harbour basin, now known as the Duncan Dock, was nearing completion and that most of the troubles experienced were occurring within the new basin. Construction had begun in 1938 with the erection of a steel sheet-piling mole to bound the basin on the seaward side, and with the reclamation of the foreshore and the building of a quay wall on the landward side. By the end of 1939 the basin area was sealed off from the bay except for the opening that was to be the final entrance, and by the end of 1941 the reclamation had advanced to a stage where the basin had almost assumed its final rectangular form.

It is to the credit of Mr. George Stewart, formerly Senior Lecturer in Civil Engineering at the University of Cape Town, that he consistently warned of the Range problem and advocated a model investigation before a decision was reached as to the final design of the harbour extensions.* But the crisis had not then arisen and the advantages of model research were not sufficiently apparent to outweigh the mature considerations of experienced harbour engineers and consultants. Even when the crisis developed, technical opinion wavered, but it seems that it was the insistance of a non-technical man on the need for a scientific investigation. that led the Administration to think in terms of a model study. For to the Port Captain of the time, Captain Weller, belongs the credit - if credit be ever due - of having repeatedly pleaded the cause of a model investigation until his suggestion was finally heeded. A model investigation was authorised in the latter part of 1941, the research was commenced and monies were voted for the construction of

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* Stewart: Evidence before Table Bay Harbour Improvements Committee. Sept., 1921, [2], p. 269: also 'Harbour Design with Special Reference to South African Conditions'; Proc. S.A.Soc. C.E., v. 33, 1935, [3], pp. 153-159.

a model and laboratory.

Returning to the question of the nature of Range action we may now consider briefly in what light it was regarded by local opinion prior to the start of investigations in 1942.

It was a matter of common observation that Range occurred generally after, or during, heavy weather borne in from the north-west during winter-time; but it was by no means dependent on these conditions and could occur in windless weather and sometimes even in the summer months. The breaking-adrift of the 'Mauretania', which we have already cited, occurred on a calm, clear night.

The ranging of ships was known to involve an intermittent, leisurely, vertical and horizontal movement, produced by disturbances of water in the harbour basins and obviously associated with the visible 'run' of water through the basin entrances. Different berths had varying degrees of susceptibility to Range disturbances and nautical opinion was almost unanimous in indicating which the most troublesome berths were.

It was quite clear that the phenomenon was not a new one related only to the construction of the new basin, for it had always been prevalent in the old basins, apparently even from the time the first dock was completed. Nevertheless the troubles were held to have been accentuated by the completion of the new mole, which, by common consent, was considered to have deprived the original harbour of its natural shock-absorber against heavy seas - the bight now reclaimed from the bay. Range, it was maintained, had not been particularly noticeable in the south basin enclosed by the old random-block mole, (now enveloped within the new Duncan Basin), and this was held to be evidence of the sponge-effect of the bight in absorbing wave energy, in the days before the reclamation.

The origin of 'run' and Range-action was commonly ascribed to north-westerly swells curving round the end of the breakwater and breaching the entrances of the basins. The interrupted end of each roller passing the breakwater, in virtue of the head of water it acquired above general sea level in the lee of the breakwater, was considered to flow laterally and penetrate the mouths of the basins. Having once entered the basins the waves were assumed to reflect off the vertical quay walls and cross the docks from end to end and from side to side until their energy was dissipated. Coupled with this, however, was believed to be an effect of wave reflection from the Milnerton shore of the bay.

For the purposes of explaining the 'run' in the basin entrances, port officials lent to the theory that currents were induced along the shore of the bay as a result of the accumulated bodies of water brought into the bay by the swell and the wind; these currents were supposed to be deflected into the harbour basins. But nautical opinion seemed unable to advance any concrete evidence as to why it retained the impression of a reflection effect from the shore, for it was generally conceded that currents in the bay at all times were almost negligible and hardly worth consideration.

An invariable feature of Range action and one by which its prevalence was usually judged by port staff, was the often-powerful, periodic flux of water through the narrow channel connecting the old Victoria Dock with its inner harbour (Alfred Basin). On occasions of severe Range action the current through this connecting channel was likened to that of a millrace, but how such a current could be caused by the penetration of normal swell, weakened after expansion round the breakwater and after reflection from the shore, especially when the entrance of the Victoria Dock was so well protected within the lee of the breakwater, could hardly be explained even on the supposition that currents were induced by the swell in the bay. Yet such an explanation was incompatible with other evidence that currents were always inconsiderable. In the face of these difficulties nautical and technical opinion admitted that it was largely mystified as to what actually took place: it believed, however, that the phenomenon as a whole was probably caused by storms far out to sea and that the conditions were essentially related to the swell that entered Table Bay.

Such then was the substance of current knowledge of the Range phenomenon. In this thin crust of knowledge the seed of the research was sown, and into more stable depths it drove its roots, and grew and prospered, we believe, to burgeon forth with fruit. But whether those fruit be withered and sour, or whether they contain some nourishment of worth, must, we fear, be left to the final judgement of whosoever delves within these pages.

PART I

THE PHENOMENON OF RANGE

> "I could never content my contemplation with those general pieces of wonder, the Flux and Reflux of the Sea,..."
>
> —Sir Thomas Browne,
> Religio Medici, (1643).

CHAPTER I

THE HISTORY OF RANGE ACTION AT CAPE TOWN.

> "Since the beginning of June till the middle of October such heavy storms from the north-west have raged in Table Bay that the vessels could hardly have been preserved from being wrecked in consequence of the frightfully heavy seas rolling right towards the spot where the large ships generally ride at anchor."
>
> —— Jan van Riebeeck,
> Diary at the Cape (1653).

1. The Cape of Storms.

From the very beginning of recorded history at the Cape mention is made of the frequent and violent storms from the north-west visiting Table Bay in the winter months from May to September. These were so greatly feared by the early mariners that they lacked no inducement, even to the extent of preferring to brave the horrors of scurvy, to evade the dangers of a call at Cape Town in the winter season. The storms took a dreadful toll of lives and shipping: in 200 years, from 1657 to 1857, it has been estimated* that over 2000 lives were lost by shipwreck, no less than 660 persons having perished on one occasion and over 300 on another. With good reason the early Portuguese navigators called the Cape '<u>Cabo Tormentosa</u>' -- the Cape of Storms.

The winter gales descended upon Cape Town with terrific force, whipping up tremendous seas: often too the gales were of long duration, continuing unabated over several days and nights. The gale of 1697 wrecked two East Indiamen at the Salt River mouth with the loss of over 300 lives; that of 1722 was even more disastrous and destroyed 10 ships of whose crews 660 persons were drowned: another four ships succumbed to the gale of 1728 and 170 lives were lost, while in

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* Table Bay Harbour Board: 'The Harbour Works of Table Bay from 1656 to 1895, (Cape Town), 1895. [4].

1737 yet another 10 ships were driven ashore resulting in the drowning of 208 seamen; shortly thereafter in 1740 a single ship with a valuable cargo was wrecked with the loss of 20 hands. The grim toll of disasters was augmented by further losses of 7 ships in 1788, 7 ships in 1790, and 8 in 1799, which included the 64-gun frigate 'Sceptre' of whose crew 290 perished; nor was this all, for the gale of July, 1831, wrecked 6 more ships. An unprecedented gale in June, 1862, lasted for 17 days, only to be followed in May 1865, by one so catastrophic that it wrecked no less than 18 ships and caused the loss of 60 lives. By repute, a still more terrible gale, which lasted for 5 days in July, 1878, drove 5 ships ashore and would have done infinitely greater damage had not the harbour by then afforded some measure of protection in the roadstead.

These gales, playing with unbroken fury over a great expanse of ocean to the westward of Cape Town, raised enormous seas, the power of which, Scott Russell, whose studies of waves are now classic, vividly portrays in the following passage[*]:-

> These rollers, or ground-swell, did not merely oscillate up and down and backwards and forwards; and they could not be eluded, or turned back, by giving to the wall [breakwater] a particular curve suited to the form of a cycloidal oscillation. These great waves of translation constituted a vast mass of solid water moving in one direction with great velocity, and this action was nearly as powerful at a great depth as at the surface.

2. The Provision of a Breakwater at Cape Town.

Against the fury of these seas the only natural protection in Table Bay was the promontory of land, now known as Mouille Point, and the rocky outcrop of Robben Island

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[*] Cf. Thomas Stevenson: 'Design and construction of Harbours', (Edinburgh), 1864, [6], p. 79.

(Fig. 1.), but, as we shall see more clearly at a later stage, neither of these topographical features could in themselves provide sheltered water against the inroads of wind and sea.

The earlier of the disasters we have cited were, unhappily, viewed by the Dutch East India Company with less concern from the point of view of the human losses than of the property losses, and it was not until the gales of 1737 and 1740 had caused the loss of merchandise and specie respectively valued at £160,000 and £500,000, (following upon losses of cargo valued at a million pounds in 1722), that the Company was stirred to take action.

The natural anchorage for ships was, of course, within the lee of the Mouille Point headland and from the extremity of this therefore the construction of a mole was begun in 1743. But the Company's evasive tactics in attempting to minimise its own liabilities in the undertaking soon resulted in the abandonment of the work. The imported slave labour suffered disastrously from deaths; the supply of stone to the works, dependent as it was on cartage extorted from whoever brought his produce into town for sale, was terminated by a crop failure resulting from the depredations of locusts; and the burghers finally refused to pay the tax levied against them to meet the expenses of the work. In all, about 350 feet of the mole were constructed, but the mound was soon levelled by the sea and never offered any effective protection to shipping in the bay.

Not until after the British occupation of the Cape was any further attempt made to provide safe refuge for ships. At the time of the gale of 1831 the only seaworks in existence was the original (or its successor), stone-filled crib-jetty erected near the Castle in 1656, but the construction of a new stone pier at the foot of Bree Street was undertaken at once. This work was superseded in 1836 by three jetties, respectively the north, central and south, along the western shoreline of the bay within the lee of the Mouille Point headland (Fig. 2), which were completed in 1842, and by an additional stone pier near the old Amsterdam Battery, built in 1845. But by 1853 all three of the former jetties had suffered severely from the winter gales, and it was found necessary to remove the southern one. The central jetty was extended in 1857 and from this and the northern jetty the entire trade of the port was conducted.

These jetties, however, did not in themselves afford any material protection to ships against winter storms, being merely conveniences to facilitate the handling of cargo to and from the ships.

More serious schemes for a harbour of refuge had been proposed from as early as 1823, but for one reason or another they were not adopted. In 1857, however, the designs of Capt. Vetch, the harbour Surveyor to the Admiralty, were accepted and sanctioned by Colonial Act No. 11 of 1857 and by another Act of 1858 (Fig. 1). At Vetch's own suggestion Sir John Coode was appointed Engineer-in-Chief of the proposed works and Coode appointed a Mr. Andrews Resident Engineer on the site. Curiously, Vetch's plans were never implemented, for a parliamentary commission in 1859 decided to invite Coode to submit plans for a less expensive harbour that would meet immediate needs. Coode therefore prepared a design, based on the suggestion of Andrews, which provided for a land-locked basin to be excavated from rock near the Amsterdam Battery, the spoil from which was to be used for a breakwater sited a little to the north of Vetch's proposed breakwater, but with different orientation. These plans were accepted and work on the breakwater was commenced in September, 1860.

It is noteworthy that Coode does not seem to have seriously entertained the idea of locating the breakwater at the extremity of Mouille Point, where the original mole of 1743 was sited, and in this he was influenced no doubt by the consideration of securing some protection from the promontory itself and by his conservative view of the possibilities of the port's expansion. In the succeeding years the opinion has been voiced more than once that a supreme mistake was made by Coode in locating the breakwater on its present site*. Insofar as the Range problem is involved, it may be of interest to examine this contention at a later stage in this treatise.

3. The Growth of Table Bay Harbour.

The construction of the breakwater to a length of 1790 feet was completed by 1869, and the internal dock was then officially opened and named the Alfred Basin. We may note in passing that the great gale and seas of May 17th, 1865, were credited with having moved 60,000 tons of stone in the breakwater by washing down 270 feet of the headworks and shifting 70 feet of the bank towards Cape Town; but no

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* Cf. for example, the Evidence of Mr. F. Robb, Superintendent, South African Railways & Harbours, given before the Committee on Schemes for the Development of Cape Town Harbour, September, 1921, [2], p.311.

material was actually carried away and lost in the process.

By 1878 the harbour had expanded to the size and shape of Fig. 2, when the terrible gale of July 18th-23rd, 1878, proved that it was not yet adequate to the task of sheltering ships from the winter storms. Coode then submitted plans for further increasing the area of safe water, and in deference to the newly elicited fact that the great gale had blown for part of the time from N.N.W. and due North*, he proposed to cant the breakwater extension with a view to economising on the length necessary to shield the anchorage.

Coode's proposals for the breakwater extension and an outer basin, abutting on the Alfred Basin and the completed breakwater, were eventually adopted with slight modifications, and by 1900 the harbour had assumed the configuration and extent of Fig. 3. Further great gales on June 17th, 1885, and June 30th, 1889, were weathered without much trouble, though in the latter storm one ship that happened to be lying outside the protection of the breakwater was driven ashore.

4. The Ascendancy of the Range Phenomenon.

It would appear that the phenomenon of Range, then known as 'scend' or 'run', manifested itself within the Alfred Basin from the time of its opening in 1869. Although there is no positive evidence of this we find the first allusion to its existence in Sir John Coode's report of November 30th, 1878, in which he advocated a breakwater extension not only to provide a larger sheltered anchorage,

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* Evidence of Mr. Jenour, Resident Engineer, Table Bay Harbour: Report of the Commission appointed to Enquire into Recent Wrecks and Disasters in Table Bay, October 2, 1878, [6].

but to

> " exclude from the Alfred Basin much, if not all, of the 'scend' or undulation which has sometimes been complained of as having given rise to inconvenience."

But the extensions of the breakwater that had been effected up to 1900, together with the provision of the outer Victoria Basin, (Figs. 2 & 3), had not, as expected, eliminated the Range disturbances; rather had the latter become a prima causa for still further extending the breakwater beyond the limit then attained. Thus the consulting engineer, Sir William Matthews, in 1900, advocated* further extending the works to reduce the

> " oscillation now so seriously felt in the Victoria and Alfred Basins."

He mentions that on July 4th, 1900, the Bucknall steamer 'Cumeria', which sought entrance to the graving dock in badly damaged condition, was unable to enter for 24 hours because of the heavy 'scend' prevailing at the caisson gate. Later, when this same steamer was ready to leave dry-dock, she was delayed another 24 hours for the same reason, notwithstanding the fact that other ships had been kept waiting many weeks to enter the dock.

By now nautical opinion was becoming alarmed at the possible navigating difficulties attendant on an extension of the breakwater along its new alignment (Fig. 3), and the consultants therefore proposed to cant the extension 15° to the northward, although in earlier reports they had recommended extension along the line of the existing works.

The necessity for extending the breakwater as a deterrent against Range action was opined also by Messrs. W. C. Methven and R. H. Hammerley-Heenen, consultants, in

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* Coode, Son & Matthews: Report on Existing and Proposed Works, Table Bay Harbour, July 25, 1900, [7].

1902, from whose report* we quote the following significant passage:-

> " Our own opinion is that a further extension for at least 1000 feet is necessary, not only in connection with the new [proposed] works, but in order to minimise as far as possible the 'run' which is found so exceedingly inconvenient and dangerous in the existing basins in certain conditions of sea. We also consider that Messrs. Coode, Son & Matthews were right in proposing that the extension should continue on the present line as shown upon their plan of December, 1897. Their report of July 25th, 1900, shows that, in subsequently recommending the continuing of the line northwards and thus forming a re-entrant angle on the north side, this was done in deference to nautical opinion."

It is interesting to record that Methven and Hammersley-Heenen in this report advocated the expansion of the harbour by the construction of a large new basin and the reclamation of sea from the bay, along lines which anticipated the Duncan Basin of today. In respect of their proposals they say:-

> " With regard to exposure the fact is fully recognised that until the completion of the outer protecting mole enclosing the harbour [comparable with the Eastern Mole of the Duncan Basin], some inconvenience will necessarily be felt from the 'run' or 'scend' during northerly seas and from the 'jabble' caused by south-easterly gales."

5. Range Action as a Factor affecting Harbour Development.

The proposals to extend the breakwater by 1000 feet or more in a continued straight line were ultimately adopted, though not before the question of the direction of extension had received mature consideration over a considerable span of years. A committee appointed by the Minister of Railways and Harbours in 1921 to investigate schemes for the development of the harbour finally examined the matter very thoroughly by calling for evidence from all persons competent to express an opinion on the subject. Nautical opinion appeared to be somewhat divided on the controversy of navigation difficulties, but engineering opinion was so emphatically opposed to a re-entrant angle in the line of the

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* Joint Report to the Table Bay Harbour Board, 1902, [8].

breakwater that the Committee felt compelled to recommend extension in a straight line*.

The Committee at the same time sifted voluminous evidence for and against various alternative schemes of development for the port. It would be outside the purpose of this paper to discuss the different schemes that were considered at that time, but the Methven/Hammersley-Heenen proposals do not appear to have been entertained. It is noteworthy that the bulk of opinion was averse to the northern scheme, which proposed a new basin between the old breakwater and a new one to be constructed at Mouille Point on the site of the ancient mole of 1743. The Committee in its final recommendations, while apparently diffident about expressing itself on the relative merits of the alternative southern schemes, defined itself as opposed to the northern scheme. In the author's humble opinion, (with the knowledge before him that has since been gleaned from the Range research), it was unfortunate that the northern scheme was so summarily rejected purely on the basis of conjectural opinion when so many expressions of opinion savoured of careful scientific investigation and experimentation before deciding the location for a new basin.

That the Committee was wide awake to the effects of Range action and the dangers of perpetuating them in the proposed development schemes is manifest from the large number of questions on the subject directed at witnesses. In contra-distinction to this, however, it is curious that the Committee makes no mention of the Range at all in its final report. The evidence on the nature of Range and its

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* Report of the Committee on Schemes for the Development of Table Bay Harbour, October 1, 1921,[2].

anticipated effects, as accumulated by the Committee, is chiefly remarkable in revealing how little the phenomenon was really understood, and how largely conjectural were the opinions expressed. The Committee, in leading evidence, after having had the benefit of most of the available knowledge, confessed itself largely mystified as to the true nature of the phenomenon. Perhaps for this very reason it was thought advisable not to attempt analysis of the evidence in the report to the Minister; it was apparently sufficient that opinion had been unanimous that the breakwater extension would have a salutory effect on the Range rather than otherwise; and as the Committee avoided compromising itself with any immutable recommendation as to a best development scheme, except a purely negative one, it was not implicated to such an analysis. We may, never-the-less, with some benefit to our theme, in the Third Chapter, undertake some analysis of the statements of witnesses who gave evidence before the Committee.

Before action was taken on the construction of a new basin, the opinions of engineering consultants were obtained. Sir George Buchanan's report[*] of 1923, however, makes no mention of the Range, and Mr. F. S. Wilson's report[†] of 1925, which favoured the southern scheme, has only an implied reference to the Range by drawing attention to the necessity for a light protecting mole to shield off the seas rebounding off the coast to leeward of the harbour. It is noteworthy that Messrs. Coode, Son & Mathews in their report of 1900[§], considered that no encroachment on the fore shore between the South Arm Root and the city should be made

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[*] (Of Messrs. Meik & Buchanan): Report on Table Bay Harbour, 1923, [9].

[†] Coode, Fitzmaurice, Wilson & Mitchell: Report on Table Bay Harbour, January 12, 1925, [10].

[§] Loc. cit. (ante p.16), [7].

in any future development.

In the years that immediately followed, the construction of a random-block mole, to form a south basin adjacent to the Victoria Basin, was undertaken, and by 1932 was complete, as, by then, was also the extension of the breakwater. The harbour at this stage (1932) therefore took the configuration defined in purple in Fig. 2.

The south basin had hardly been completed as an enclosure before engineering opinion was consulted again as to the form of its further development. The Harbour Affairs Commission* of 1934, appointed to expatiate on this, does not, however, reveal from its report that it was even aware of the Range phenomenon.

From 1935 to 1938 there followed a period of intense activity in planning relative to the question of the further expansion of the harbour, but it is quite outside the domain of this treatise to follow the arguments which led to the abandonment of the south basin and the adoption of the scheme which was ultimately to result in the Duncan Basin of today. Colonel J. F. Craig, who designed the lay-out of the Duncan Dock, may, or may not, have been influenced by the Methven/Hammersley-Heenen proposals of 1902. At any rate, he gave apparently the fullest consideration to the possible effects

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* Messrs. Nijhoff & Geertsema: Report of the Harbour Affairs Commission, November 13, 1934, [11].

of Range in discussions with eminent harbour authorities in various countries abroad*; but, if the author is permitted to make an observation hereon, it is to express the regret that the proposed developments at this stage were not subjected to model experimentation, especially when, at this time, model technique in hydraulic problems already had fully 50 years of successful application to its credit. Such an investigation might then have disclosed the advisability of expanding the harbour to the north rather than to the south; in any case, with all due respect to the experts, its indications would have been infinitely more valuable than mere experience and intuition.

Construction of the Duncan Basin was commenced in 1938 and was largely complete by 1942, though the construction of the Sturrock graving dock within it was not completed until the end of 1945. The final and now familiar form of Table Bay harbour was thus achieved in 1945 (Fig. 4).

A point of significance which should be recorded here is that in order to effect the wider, 750 ft. entrance for the Duncan Basin, which coincided with the 400 ft. entrance of the older south basin, it was necessary to remove 350 feet of random blockwork. Partial removal of this obstruction down to the rubble base, well below low-water level, was completed early in 1940, but the severe occurrences of Range action attendant on the storms of April and May, 1940, led to the replacement of the blocks and the permanent closing of the Duncan Basin entrance to the 400 ft. width. It was generally felt at this time that the narrowing of the entrance (which was completed in August, 1940), was definitely

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* Cf. "Movement of Water in Table Bay", The Engineer, Vol.167, April 1939, [12], p.481.

beneficial in reducing the magnitude of the Range disturbances, a point which we shall have occasion to discuss at a more advanced stage in this work.

6. Troubles arising from Range Action at Cape Town.

We have already referred in Section 4 to the difficulties experienced from Range in dry-docking the 'Cumeria' in the Robinson graving dock, within the Alfred Basin, in 1900. Of other such troubles resulting from incidences of Range action it has been difficult to acquire information, because so many old records were unfortunately disposed of to meet the desperate paper shortages during the recent World War. The author has been unable even to gain access to old log books of the Port Captain's office, which might have thrown light on this subject, except those, of course, of recent years, and he has therefore had to seek what information there is from other sources.

Captain John Short, ex-Port Captain at Cape Town, has disclosed[*] that in 1917, when the harbour was substantially as in Fig. 3, a tanker, moored at the Elbow in the Victoria Basin, broke adrift during severe Range Action and careered across the dock towards the East Pier. Rivets were found to have been started in her shell plating and wooden plugs had to be driven to stop the petrol leakage.

Mr. Geo. Stewart reveals[†] that in 1918 a large Australian transport, under the stimulus of Range action, broke so many ropes that she had to be taken outside the basin to the anchorage; and it would appear from what members of the nautical staff at the harbour have stated that this sort of thing happened more than once in the days before the existence

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[*] In interview with the author.

[†] Discussion on Wave Action in Harbours; Proc. Inst.C.E., Vol.209, 1919-20,[1],p.242.

of the south basin and the Duncan Dock.

Recently, since the Duncan Dock came into use, information has been more complete in regard to the effects that Range action is capable of producing*. Thus on April 29th, 1940, the dredger 'Springbok', moored at F berth in the Duncan Basin (Fig. 4), started rivets in her hull plating through impact against the fenders resulting from Range. On the same occasion, along the Eastern Mole, two rock-breakers broke adrift, and a fleet of small whale-catchers parted some 40 odd mooring ropes and were in imminent peril of being damaged. A month later, on May 28th, 1940, the 'Mauretania' of 42,000 tons displacement tonnage, broke completely adrift from C berth in the Duncan Basin after fracturing no less than 44 mooring ropes, during a severe occurrence of Range action; two tugs attempted to pin the big ship against the quay during the night while she raised steam to seek safety in the roadstead, but notwithstanding this she is reported to have ranged through 20 feet to-and-fro along the quay. These effects, it may be noted, occurred during the short period that the Duncan Basin had a nominal entrance-width of 750 feet.

On July 29th, 1940, the 'Mantola' of 15,500 tons displacement tonnage, broke a deckwinch and gangway at A berth in the Duncan Basin and had to be removed to the anchorage for safety.

A serious occurrence of Range on June 2nd, 1941 caused four minesweepers, lashed together, to break adrift from the north quay in the Alfred Basin and to jam in the connecting channel or 'cut' between the Victoria and Alfred

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* These records are to be found in the Port Captain's official papers, P.C./G/36/3, as also of the System Manager, S.A.R.& H., Cape Town, G.H.198.[13].

Basins: concurrently, the 'Clan McArthur' of 16,700 tons (displacement), moored at the northern stub jetties in the Duncan Basin (Fig. 4), crushed and splintered to destruction the floating wooden fenders and the waling of No. 2 stub, thereafter displacing the concrete coping blocks of the stub and making contact with its steel sheet-piling face, as a result of which the vessel sustained damage to her hull plating. The 'Silverteak' of 15,500 tons (displacement), also moored at the stub jetties, was responsible for crushing several more sets of floating fenders and for disturbing some of the mooring bollards.

From September 1st to 3rd, 1941, during another severe occurrence of Range, the 'Brittanic' of 33,200 tons (displacement) broke adrift from C berth in the Duncan Basin and holed her stern on the stern anchor of the 'Reina del Pacifico', which was moored at B berth. Along the Eastern Mole, 'Lt. St. Loubert Bie' of 13,000 tons displacement broke two fairleads, while 'Kawsor' of 11,300 tons and 'Glarona' of 17,900 tons displacement each broke a fairlead during berthage at the stubs. At the northern end of the mole, 'Vikings' of only 1100 tons displacement damaged her side and the coping of the wall. Altogether five sets of floating fenders were crushed to splinters at the Eastern Mole.

A claim for damages to the 'Christian Holm', which was alleged to have sustained dented shell-plating while berthed at the stub jetties on September 13/14th, 1941, was also lodged, although Range action at the time was relatively slight: this vessel had a displacement tonnage of 12,400.

During 1942 further troubles ensued. On May 27th, the 'East Wales' of 10,900 tons displacement, double-banked against the 'Stanford' at H berth in the Duncan Basin damaged her hull plating; on June 8th, the 60 ton floating crane at F berth dented her side plates and jumped the hoisting wire off the sheaves and had to be towed to the Victoria Basin for safety; on June 9th, the 'Mangkalihat', displacing 11,000 tons, was so severely damaged through impact against the fenders and the quay at J berth that a claim for £13,116 in damages was lodged and ultimately paid. In respect of this latter instance, it may be noted that the circumstances were unusual: the 'Mangkalihat', which had sustained serious war damage from a floating mine, was berthed in a state of abnormal trim, with her stern ballasted to raise her bows above water-level. Her centre of buoyancy being thus transferred towards the stern, it was understandable that in the lateral surge of the Range the bows should have pivoted about the stern with a whip action.

On June 19th, 1942, there occurred perhaps the worst incidence of Range on record. In the Victoria Basin a gangway was broken, 3 floating fenders were smashed and 15 mooring ropes parted, while in the Duncan Basin no less than 7 floating fenders were crushed and 69 mooring ropes fractured. The largest ship in the Duncan Basin at the time was the 'Almanzora' of 23,200 tons displacement at C berth, and in the Victoria Basin, the 'City of Manila', displacing 15,600 tons, but although both basins were practically full of shipping, no actual damage to ships appears to have been sustained. The situation would probably have been very different if ships of larger tonnage had been present. It is curious, nevertheless, that the 'Arndale', displacing 14,600 tons at the northern stubs in the Duncan Basin, parted only 2 ropes: floating fenders at the stubs had by this time been dispensed with in favour of rolling fenders utilising old motor tyres of large size, and there is no record of fenders having been crushed at the Eastern Mole.

From August 20th to 22nd, 1942, floating fenders mysteriously disappeared from several occupied berths in both the Victoria and Duncan Basins. Thus four fenders were reported missing from the 'Queen City', double-banked at H berth, and one fender from the 'Staffordshire' at E berth, while a rubber fender at the Elbow, Victoria Basin, was also reported vanished. Subsequently three of the missing fenders were located near the yacht harbour in the Duncan Basin. During this time the 'Empire Advocate', displacing 12,300 tons at B berth, broke a ship's fairlead.

Under phenomenal conditions of 'run' on October 8th, 1942, the tug 'Buffalo' collided with HMS. 'Spindrift' off the end of No. 1 Jetty in the Victoria Basin, and the 'City of Canton', entering the Duncan Basin under guidance from the tug 'T. H. Watermeyer', was caught in the spate of the surge through the basin mouth and was carried bodily backwards outside the harbour. The full details of this remarkable incident will be considered later when more has been disclosed on the nature of Range action. Only a short while after the 'City of Canton' had thus been ejected from the Duncan Basin, the 'Bankok II', in leaving the same basin, grazed the north side of the bullnose at the entrance, (Fig. 4), through being caught in the current.

After 1942 the magnitude and severity of Range action decreased noticeably, but there were still occasions when trouble of some consequence developed. Thus on June 30th, 1943, two minesweepers broke adrift from the north quay in the Alfred Basin in much the same way as they had done in 1941: on July 1st, 1943, 'Compiegne' and 'Marit II', respectively displacing 13,900 and 9,800 tons, sustained buckled shell-plating at the stub berths, as also did the 'Rosemont' of 9,800 tons on July 11th, 1943.

During 1944, the 'Canton' was alleged to have buckled her shell plating while lying moored at J berth on July 4th, and the 'Cap St. Jacques' apparently sustained dented plates while lying at G and H berths, as was subsequently discovered when the vessel was dry-docked, (August 11th).

In 1945, on July 30th, the 'Anna Howard Shaw' of 12,800 tons displacement broke from her stern moorings at D berth in the Duncan Basin and receded off the quay dragging the gangway with her. In attempts to re-moor her the ship's deck-winch was wrecked and for 12 hours overnight the vessel had to be pinned to the quay by a tug. Similar failures of deck-winches during remooring occurred a fortnight later on August 12th on the 'Clan Macaulay' of 15,600 tons and on the 'W. E. Christiansen' of 12,300 tons displacement, respectively at B and E berths in the Duncan Dock. Troubles of this nature were not always an exclusive feature of the winter months as may be judged from the fact that the 'King Stephen', displacing 9,800 tons at D berth, suffered a broken chock and damaged poop-railing in mid-summer, December 17th, 1945.

Other incidents since that time, apart from rope breakages, which are of fairly frequent occurrence, have been relatively minor, and while this state of affairs is to some extent attributable to the lessened magnitude of the Range phenomenon in recent years, there is no doubt that three important factors have had a bearing upon it. First, and principal, was the abandonment, as serviceable berths, of the stub-jetties along the Eastern Mole, following upon the mishaps of 1943; second was the adoption of the practice of holding ships off the quays at dangerous berths by means of off-shore anchors, and finally was the policy, strongly emphasised as a palliative measure for dealing with Range action by the results of the research itself, of mooring ships always as tightly as possible.

7. The Impact of Range upon the Reputation of the Port.

It was natural that the damage to which ships were subjected as a result of Range should be seriously regarded by the shipowners, the port authorities and the city of Cape Town alike. The South African Railways & Harbours Administration found itself suddenly faced with heavy expenses for damages as a result of the unusual concentration of shipping of large tonnages at Cape Town during the critical war years of 1940-1944. This became the subject of inquiry before a Parliamentary Select Committee on Railways and Harbours, especially in respect of the sum of £13,000 to be paid against the claim from the masters of the 'Mangkalihat'. The publicity given to this could not but fail to impress the shipping world, and 'Range' became very much more of a catchword than it had ever been in the years before.

Following upon the statements of the General Manager of Railways to the Parliamentary Select Committee in

April, 1944, explaining that researches had been in hand since 1942 to find means of solving the Range trouble, Mr. George Stewart in his presidential address to the South African Society of Civil Engineers saw fit to criticise the Administration for not having conducted the investigation long before the construction of the Duncan Basin. This precipitated considerable ventilation of views on the subject in local newspapers and in shipping and engineering journals overseas*, all of which had the effect of bringing the disabilities of the port into critical prominance.

But matters were brought to a head on November 10th, 1945, by the unfortunate incident of the 45,000 ton 'Aquitania', which, loaded with Anzac troops returning to their homeland after the war, was not allowed to dock at Cape Town, but perforce had to refuel and provision in the open roadstead of Table Bay.

The South African press fairly screamed its indignation against this slight to the good name and port of Cape Town and to the tradition of hospitality always freely extended to comrades-in-arms in time of war. Curiously, although it was announced in the press† a day before the arrival of the ship that:

> " The decision to keep the ship in the roadstead is the outcome of a series of meetings between senior officials held during the week at which the liner's draught and the range in the dock were considered.
>
> Owing to the range in the dock which might cause the liner to surge at her moorings and possibly to suffer damage, the Railways administration required indemnity against being held liable for damage caused to the ship while in Cape Town,"

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* Cf. Marsh: 'The problem of Range in Table Bay', The Outspan, June 9, 1944,[14]; Syren & Shipping (London)June 21,1944[15]; Dock & Harbour Authority(London)July,1944[16];The Engineer (London)August 11,1944,[17].

† Cape Times: Saturday, Nov. 10, 1945,[18].

it remained for some time a mystery as to who, in point of fact, had given the instruction for the ship to anchor in the bay. According to a later statement* from the British Ministry of War Transport and the Principal Sea Transport Officer, South Africa, it transpired that the master of the ship had also demanded a letter of indemnity if the ship were to dock at Cape Town, and the Director of Sea Transport, London, charterer of the ship, in his discretion, ordered refuelling in the bay. The latter's attitude is understandable since it is on record† that the 'Aquitania' was previously damaged from bumping the fenders at her berth in the Duncan Dock on a visit to Cape Town in 1943. On that occasion the owners and the Harbours Administration were indemnified by the Admiralty against repairs, reputed to have cost several thousand pounds.

The facts surrounding this case of 1945 were that throughout the 7th, 8th and 9th of November as the 'Aquitania' was approaching Cape Town, very heavy swells were impinging upon the southern coast of Africa, Range action commenced in Table Bay harbour from about noon on the 7th and reached a peak from about 01 to 18 hours on the 8th, but had more or less subsided on the 9th. It must be presumed that the British Admiralty, in the face of this knowledge and the demands for indemnity from the ship owners and the Railways and Harbours Administration, decided to run no risks of further damage being sustained and withheld permission for the ship to dock.

The incident served to illustrate the extent to which the notoriety of the Range could injure the reputation of the

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* Cape Argus: Tuesday, Nov. 13, 1945, [19].

† Cape Argus: Saturday, Nov. 10, 1945, [20].

port of Cape Town. The event produced a flood of comment and criticism, which, as we have recorded in the Preface, reacted sharply on the conduct of the research. The public demand for information had eventually to be met by an open invitation to the press to witness the progress being made at the Range Laboratory, but the echoes of this outcry were heard long afterwards in distant quarters*.

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* Cf., The Engineer, March 29, 1946 [21]; Dock and Harbour Authority, May 1946, [22].

CHAPTER II

OCEANOGRAPHIC FEATURES OF TABLE BAY.

" Sometimes violent north-west winds blow for several days together in May, June, July, August and September, and by fits in other months; the sky is then constantly clouded and they generally end in rain."

__ Abbe de la Caille,(1755).*

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8. The Winds at Cape Town.

Cape Town, by virtue of its position on the south-western tip of the African continent, is flanked by a vast expanse of open sea, and its weather is intimately bound up with the mass-movements of air that occur over the ocean. The winds that play over the Cape Peninsula and, indeed, over South Africa as a whole, are dependent on the seasonal changes of the high-pressure belt which girdles the southern hemisphere between parallels of latitude embracing the Union of South Africa, south of Capricorn.

As Fig. 5† shows, this high pressure belt is fully contracted in mid-summer, January, as air is drawn away to its big concentration over the Asian land-mass in the northern hemisphere, and air currents, running anti-clockwise across the isobars, yield the prevailing south-east winds along the coastal region of South Africa. With the approach of winter there is a gradual flow of air back to the southern hemisphere and an intensification of the high pressure areas over the oceans. By mid-winter, July, the southern flank of a closed isobaric loop lies over Cape Town and the prevailing winds are slightly north-west.

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* 'An Account of the Astronomical, Geographical and Physical Observations made at the Cape of Good Hope in 1751, 1752 and 1753, by Order of the French King', Gentleman's Magazine (London),1755,[23].

† This is interpolated from data given in Goodall and Darby's 'The University Atlas',(London),1940,[24].

This general system of seasonal air-movement is complicated by frequent irruptions of travelling depressions or cyclonic storms in the steep barometric gradient south of the high-pressure doldrums. These depressions will be considered in greater detail in a later part of this work, but for the present it suffices to say that they spring from the central South Atlantic and tend to follow each other in families on an eastward drift which carries them generally some distance south of the African continent. Their winds circle clockwise around the depression-centres and they often cover such a wide ambit that their effects reach over the South African coast bringing to Cape Town much of its winter rain and intense north-west winds. Absence of rain in summer at Cape Town is to a large extent accounted for by the southward trend of the high pressure belt and the corresponding shift of the travelling depressions nearer to the south pole. A feature of the passage of a travelling depression over Cape Town apart from a falling barometer is the sharp drop in temperature accompanied by a sudden veering of the wind from north-west to west or south-west.

It is recorded* that during the great gale of May 17th, 1865, when 18 ships were wrecked in Table Bay, the barometer at Cape Town fell to the unprecedented low figure of 29.580 inches, while gale velocity between the hours 06 and 22 was never less than 40 mph and for a large part of that time was slightly above 50 mph, its direction being almost due north. The inference is that the track of a travelling depression ran very close to Cape Town and that the full fury of the cyclonic storm was meted out on the city and anchorage.

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* Royal Observatory, Cape Town.

In summer the prevailing winds at Cape Town are S.S.E. and they are frequently violent and of long duration. Intermittently, sea-breezes from the west and south-west occur in the mornings and usually back round to south-east off the land in the afternoons. South-east gales accompanied by heavy nimbus cloud on a falling barometer are known locally as 'black south-easters' and usually bring with them short spells of rain and cold weather.

9. Ocean Swells affecting Table Bay.

Table Bay is wide open to the influences of wind waves and swells from three principal diagonal directions, north-west, south-west and south-east. As Figs. 1 and 5 will show, it is in large measure protected from inroads from the south and south-east, but is very vulnerable to penetrations from the north-west, west and south-west.

The dangerous seas of which mention was made in section 1, are whipped up by the north-westerly gales accompanying the travelling depressions. According to whether the winds are local or distant, the incoming seas tend to comprise wind-driven waves or swell, or both, the term 'swell' being used in the sense of a wave propagation of energy from which the generating force has been withdrawn. Heavy seas are often encountered in Table Bay in locally calm weather, and their origin then lies in some disturbance far distant, the effects of which are propagated in swell.

From statistics collected by the Admiralty Meteorological Office*, Simonstown, and represented in Fig. 6 as applying to an area of ocean between parallels of latitude 30 to 40°S and of longitude 10 to 20°E, it would appear that in winter

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* 'Weather on the Coasts of Southern Africa', Vol II, Parts 2 & 4, (Cape Town), 1943, issued by the Chief Naval Meteorological Officer, South Atlantic, [25].

time Cape Town is subject to south-westerly swells for the most part (average frequency about 55%). South-east swells have a frequency of about 25% in the same period, and north-west swells about 8%, confused swells, presumably of a westerly nature, accounting for perhaps 11%. In summer time (December to February), it will be seen, south-east swells (frequency 37%) increase at the expense of north-west (only 1%) and south-west swells, but the latter, with a frequency of 51%, still predominate.

10. Tidal Conditions at Cape Town.

With some interest we may quote the Abbe de la Caille's record* of his observations of 1751/53 on the tides in Table Bay:

> " The new moon makes high water at the Cape at half an hour after two in the afternoon and the tide seldom rises more than 3 feet, except after a hurricane or some other extraordinary cause".

There is not much to be added to this succinct description after 200 years except to say that the tidal range at springs averages about 5 feet, though it can on occasion reach 6 or even (very rarely) 7 feet, while the range at neaps averages perhaps 2 feet. The semi-diurnal tides are of about equal magnitude and the diurnal component is very small with a range not exceeding 6 inches. As will be discussed later, there is evidence of an interesting slow fluctuation of mean sea level in conformity with barometric pressure, which, however, has no relation to the tides.

11. Ocean Currents in Table Bay.

The principal ocean currents of the South Atlantic are somewhat similar to the trade winds in that they revolve

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* L. c. (ante p.32), [23], p.513.

round the centres of high atmospheric pressure, motivated by the earth's rotation and the friction-drag of the winds. Thus the currents tend to circle anti-clockwise in the South Atlantic, and the west coast of southern Africa is fed with cold water from the south polar latitudes.

Table Bay is affected by the in-draught of this cold (50° Fahrenheit) Benguela current and to some extent by the over-shoot of the warm (60°F.) Agulhas current which runs down the east coast of South Africa until thwarted by the former current off the Cape of Good Hope. The degree to which one or other of these currents dominates seems to depend on the prevailing winds, the warm current gaining some advantage in strong south-east gales and the cold current having complete ascendency in north-west weather.

The main Benguela current has an average northward drift of only about 1 knot, and as may be expected, the currents in Table Bay are correspondingly feeble. Information on currents in Table Bay, given in the "African Pilot" of 1922,[*] refers to the 'jetties' and the 'Amsterdam Battery', landmarks long since fallen into disuse, and therefore suggests that the text has been taken over without revision from observations made in the 1860 period. Later observations on currents were made by Capt. C. D. Perry, R.N., in 1887 and by Mr. Lacy Good in 1894, but they all concur in showing that currents in the bay are relatively weak. To quote Capt. Perry[†],

> ''The outcome of all the observations taken in the course of my enquiry may be briefly summed up as follows - The general ordinary course of the current is from Green Point to the breakwater - thence south along the Cape Town side and round the bay away to the north. The current is not strong, 3/10 of a knot being the highest rate measured, and is easily turned aside or driven back altogether by local eddies and drifts set in motion by winds that often do not blow home to the port. The rising and falling of the tide does not seem to affect the currents in any degree; a look-out was kept for tidal influence but none noticed.''

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[*] African Pilot, Part II (1922), [26], p.303.

[†] Perry: 'Report on the Currents in Table Bay from Observations carried on during the Months of March, April, May and June, 1887, [27].

Neither the measurements of Mr. Lacy Good nor any subsequent observations depart from this general picture. However, Perry mentions that there was a tendency for the current (especially the undertow) to divide after bearing south-west from the end of the breakwater and reaching the shore near the Salt river mouth. The right-hand stream turned westward, scouring the Central Wharf and the south side of the breakwater (cf. Figs. 2 and 3), while the left-hand stream headed north along the coast. This is confirmed by the description in the African Pilot. Perry further remarks that:

> "With a long ground swell from the northward indicating strong winds in that quarter, although it was perfectly calm in the vicinity of the port I have found a current from the northward down along the coast sweeping round the bay and out past the breakwater toward Mouille Point at a rate of 1625 ft per hour. Whilst with the swell coming in from the westward I found the current running in the opposite direction at a rate of 1660 ft per hour,"

all of which is cited in evidence that the normal currents are easily affected by superimposed wind-drifts.

Mr. Lacy Good's investigation of the currents in Table Bay remains a model for this type of work. His conclusion regarding their impotence is aptly summed up by Messrs. Methven and Hammersley-Heenen*:

> "The exhaustive investigations and records made by Mr. Lacy Good, A.M.I.C.E., in 1895 prove that currents do not exist and that what there are are so irregular and intermittent and of so feeble a character, as to place them outside the necessity of consideration..."

12. The Configuration of the South Atlantic Basin.

We shall have cause at a later stage in this work to consider the influences of the ocean-basin of the South

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* L.C. (ante p. 17), [8].

Atlantic, bounding on the coast of South Africa. Some idea of its general configuration, therefore, seems appropriate in this chapter.

Fig. 7 gives approximate contours of the sea-bed, west and south of the southern portion of Africa, as far as the mid-Atlantic ridge*. This ridge, which reaches the surface at isolated points such as Tristran da Cunha and St. Helena, virtually divides the southern ocean into two compartments. It curves in streamline fashion round the southern tip of Africa at a distance of some 1700 to 1800 miles from the coast.

A submarine spur, taking root on the west coast of Africa near the mouth of the Cunene River, and jutting out towards Gough Island, forms in effect a northern boundary to the ocean-basin immediately west of Cape Town.

It is of interest, in passing, to note that the possibility of the ocean-basins being a consequence of the genesis of the moon, according to Darwin's theory† of the eruption of part of the earth's mass under tidal influences, was visualised by Fisher§. His view that the void would be filled by an influx of magma from below, and by fragmentation and drifting of the remaining crust, would explain the existence of the Atlantic channel and the mid-Atlantic ridge. The latter divides the Atlantic ocean almost centrally from Greenland to Antartica and appears to be obvious evidence of a rift between the continents on a line conforming with the earth's

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* Based on Goodall & Darby (l.c. ante p. 32), [24].

† Sir George Darwin, 'The Tides and Kindred Phenomena in the Solar System', (London), 1911, [28], pp. 272-317.

§ Osmond Fisher, 'Physics of the Earth's Crust', (London), 1889, [29], pp. 336-341, 380.

axis of spin. The mythical conception of a lost continent of Atlantis has now been exploded by recent scientific expeditions which have been surveying the mid-Atlantic ridge*.

13. The Topography of Table Bay.

Much of the Cape in the neighbourhood of Cape Town is mountainous and of bare rock structure, the intervening valleys comprising white sand with a high percentage of shell inclusions of obvious marine origin. There is evidence in the various raised beaches to be found in the Cape that within man's existence the sea level was some 400 feet higher than it is today†. The withdrawal of the sea could be accounted for by the gradual elevation of the land mass and possibly also to some extent by the trapping of increasing proportions of moisture by aggregation on the polar ice caps§, but a stage would be reached where the play of the tides between the rocky island of the Cape Peninsula and the mainland over shallowing ground would throw up a sand bar, resulting in the formation of the Cape Flats as we know them today, (Fig. 7).

Table Bay is flanked with this sand accumulation on its east side between the rocky escarpments of Blaauwberg Strand and Robben Island on the north and of Sea Point and Mouille Point on the south. As may be seen from Fig. 1, the original shape of the bay was not unlike a horn with its vertex between the Castle and the Amsterdam Battery, but in

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* Cf., Time, October 6, 1947, [30].

† Cf. Abbe H. Breuil: 'The Old Palaeolithic Age in relation to the Quaternary Sea Levels along the Southern Coast of Africa', S.A. Journal of Science, 1946, [31].

§ Cf. Sir Napier Shaw: Manual of Meteorology (Cambridge) 1942, [32], Vol. III, pp. 181 & 189.

sectional profile, now that the tip of the horn has been reclaimed from the sea, the bay is very like a semi-ellipsoidal bowl into which openings have been cut on two sides, along the major and minor axes (Fig. 8). Indeed, on this analogy the dimensions of the bowl would be 46,800 feet along the major axis and 31,200 feet along the minor, giving a dimensional ratio of very nearly 3 to 2.

The shape of the sea bed in the bay is shown in both Figs. 1 and 9, the depths and contours of the former being those of an early survey, (circa 1846), and of the latter those derived from the soundings of Commander Dalgleish in 1933. The maximum depth of the west channel at its narrowest point is 120 feet and that of the north channel 50 feet.

From all accounts the major portion of the sea-bed of the bay is of bare rock. During the reclamation of the foreshore for the building of the Duncan Basin (Figs. 2 & 9), very little silt could be gathered by the suction dredgers from the roadstead and most of it had to be obtained from the north side of the breakwater or from close inshore.

14. Erosion and Silting in Table Bay.

The earliest marine survey of Table Bay seems to have been made by Moller and de Heere in 1729 and it was followed in 1786 by one executed by Veelwaard and Bohn. The latter's chart gives the soundings in toises (6 1/3 feet approximately) and seems reasonably accurate, and by comparing its depths with those of Capt. Belcher's survey of 1846, Sir John Coode's of 1877, Mr. Lacy Good's of 1895, and Commander Dalgleish's of 1933 (Fig. 2), it would appear that the portion of the bay in the immediate vicinity of the harbour was much deeper in 1786 than in any period since. Obviously in the early days the weak current, of which mention has been made in Section 11, together with the oblique surf that is encountered along the west coast near the Amsterdam Battery, was sufficient to keep that portion of the coast bare of any sand deposits. However, in the dead water of Rogge Bay quite considerable sandbanks existed. Considerable shoaling must have taken place in the first half of the last century to cause the contours to recede as shown in Fig. 2, and this is difficult to explain purely on the grounds of the construction of the jetties. Slight further recession of the contours occurred up to 1860 after which they began to advance again slowly, even in the face of the main harbour works which from this time on began to push out from the rocky promontory north of the Amsterdam Battery. In spite of this, shoaling seems to have been continuing progressively close inshore, no doubt as a result of the advancing reclamation off Rogge Bay, and we find the rocks between the Castle and Fort Knokke, which were exposed in 1877, silted over by 1895.

The harbour designers were fully awake to the dangers of silting, but in advancing proposals for the harbour works in 1856, Capt. Vetch* dismissed the matter on the grounds that:

> "The only solid or stone jetty in the bight of the bay is scoured out and partially undermined on the east side and has been sanded up on the west side".

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* Report of Capt. Vetch on Harbour Works in Table Bay, Aug. 27, 1856, (Blue Paper, 1859), [33].

Later, in 1860, just before the construction of the breakwater, Sir John Coode* expressed himself as satisfied that silting would not be a problem, and remarked that some rocks on the western side of the bay had the same appearance as described in 1752. A later report of Coode's in 1877 established that there had in fact been no silting since the commencement of operations. Yet another enquiry into the possibilities of silting having occurred was conducted by a commission consisting of Capts. Perry, Bainbridge and Freebody in 1885, but it reported† no appreciable changes in water depths near the harbour. This evidence confirms Fig. 2 that from 1860 on the funnel of the bay was scouring rather than silting.

Having regard to the non-existence of appreciable harbour works in 1846 which preclude the possibility of the latter being wholly responsible for the changes, we are led to conjecture why such considerable shoaling should have occurred at the head of Table Bay in the interval between 1786 and 1846-60; further why the bay-head should be tending to deepen again from 1860 onwards when the increasing protection from the breakwater and the expanding harbour works would seem to suggest otherwise. Since 1933, even before the reclamation and construction of the Duncan Basin, steady erosion was in progress along the Paarden Eiland shore. It is true that this could be attributed to the increased wave energy deflected by the breakwater on to that part of the coast, but the existence of

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* Mr. John Coode's Report of 30th November, 1859, on the Proposed Harbour of Refuge in Table Bay, (White Paper, Cape Town, 1860), [34].

† Report of Commission assembled by Table Bay Harbour Board re Changes resulting from Extension of Breakwater in Table Bay and Condition of Bay as a Safe Anchorage, (Cape Town, 1885), [35].

erosion far north of the Diep River mouth (Fig. 9) tends to offset such an explanation as being the only one. There seems to be evidence then of a possible cyclic change in silt and scour extending over a very long period of years.

This apparent periodic change in depths is of considerable interest and raises the question whether mean-sea-level is not perhaps fluctuating in a periodic manner. This theory has been advanced by Mr. Ralph Marriott* to account for the severe erosion along the Paarden Eiland and Milnerton shore, on the supposition that a rising sea level will affect the beach slopes and necessitate the sea cutting new equilibrium gradients in the land. In the author's opinion this is very plausible inasmuch as it requires only a dwindling of the polar ice caps or, alternately, a slow change in the atmospheric high pressure belt to effect a rising sea. The Arctic ice cap and glaciers are known to be shrinking at the present time† and concurrently it has been found that the level of the North Atlantic Ocean has been steadily rising in the last 20 years at the rate of about 18 ins per century ? or about 2¼ ins per annum§. The long-term cosmic changes that are responsible for this are equally capable of producing long-period changes in the earth's atmosphere. The author ventures to suggest that there may be a slow periodic shift of the hemispherical high pressure belts to north and south of their mean positions and that such mutation would be additive in affecting sea levels and severity of storms and could also be held to

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* 'Erosion of Coast at Paarden Eiland', Report to the City Engineer, Cape Town, October 6, 1944, [36].

† Cf. F.R.Paver: 'Africa's Chances in a Warmer World', Series of y 6 Weekly Articles in The Star, Johannesburg, Dec.3,1949,et seq., [37].

§ Report of the United States Coast and Geodetic Survey,1946,[38].

account for the apparent periodic variations of rainfall, temperatures, etc., that are manifest at Cape Town and many other places*.

Whatever the circumstances, there has been in recent years very severe erosion along the whole eastern shore of Table Bay. The original marine drive which was built along the beachhead, south of the Diep River mouth, some 25 years ago has almost entirely disappeared, while the second marine drive, built about 50 yards inland of the other in 1946 is already being threatened in certain places. The rate of erosion seems to have been progressive in the last 10 years and there is no knowing where it will end.

These facts are mentioned as having a bearing on our problem, for as we shall see, the forces that are at work denuding the land are also bound up with the forces responsible for Range.

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* Cf. Discussion on 'Stormwater Drainage', Proc. S.A.Soc. C.E., Vol.42, 1944, [39], p.125.

CHAPTER III

LOCAL UNDERSTANDING OF RANGE PRIOR TO RESEARCH

> " So every degree of proceeding in a science giveth a light to that which followeth; which light if we strengthen by drawing it forth into questions or places of inquiry, we do greatly advance our pursuit".
>
> _Francis Bacon.
> Advancement of Learning(Book II),(1605).

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15. Rudiments of Knowledge.

With the background of information provided by the last chapter we may proceed to examine, in greater detail than was possible in the Introduction, the degree to which the Range phenomenon was perceived and understood by those most competent to express their views upon it, at the time that the author embarked upon his researches in 1942. As mentioned in the Preface, it was considered a first duty to consult nautical opinion and local inference, more particularly in view of the author's comparative ignorance of the subject at the time; this was, therefore, his first line of inquiry.

From the rather incomplete correspondence which passed between Cape Town and the Chief Civil Engineer's Office, where the author was at first located, it was gleaned at the outset that Range was a peculiar surging of the waters in the harbour basins, usually, but not always, associated with severe storms from the north-west. From all accounts it was erratic in nature and affected shipping in the basins rather inconsistently. The ranging of ships appeared to involve horizontal and vertical movements of tremendous power. Upon this bare kernel of comprehension grew the substance of the following first enquiries.

16. Evidence before the 1921 Committee on Harbour Schemes*.

We have already referred in a general way in Section 5 to the deliberations which the Committee on Schemes for the Development of Table Bay Harbour, appointed in 1921, gave to the Range question. This Committee consisted of Messrs. Parry, Steytler, Nicholson, Salmon and Capts. Stephens and Mathie, all of whom seem to have been properly aware of the seriousness of the Range Problem: it is an obvious inference from this that the troubles which had been experienced in the harbour of the time (still substantially the same as it was in 1900, Fig. 3) must have been very worrisome.

The Committee's first witness, Senior Pilot Capt. Johnson, who had been a pilot at Cape Town for 17 years, admitted that he could not account for the Range or 'Run' as it was then known. He said:

> " It often takes place during calm weather when there is no apparent reason for any disturbance. It may be that the origin of the 'Run' is the disturbance of water many miles from Cape Town, i.e., the after effects of a heavy storm at sea.....There are occasions when the reason for the 'Run' is very apparent, i.e., when we have a northerly gale....but we get it without any westerly or northerly wind. We frequently get it in fine weather before a strong south-easter comes along."

Johnson considered the Run was worse on the south side of the Victoria Basin than on the north side, but that it should not be appreciable in any southern basin constructed. In his view the Run partly expended itself on the beach,

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* L.c. (ante p. 14), [2].

but insufficiently to prevent its return. Run was not stronger at greater depths than at the surface, he maintained, and ship draught was not important.

Capt. Leigh, Nautical Adviser and Port Captain of Table Bay, gave some particulars of the degree of severity of the Range in the harbour as then existing (Cf. Fig. 3.). The East Pier berth was one of the best, he said; the corresponding berth at the Elbow one of the worst. The whole of the South Arm berths were bad, whereas Nos. 6 and 7 quays were good. Amplifying this, he remarked:

> " The Run along the South Arm is nothing like so bad as before the East Pier and Elbow were built. Further, Run in the inner dock, Alfred Basin, is very little inconvenience today. In the old days No. 2 Jetty was a pile jetty with a mound under it, considerably less in height than the one under the Loch Jetty. The inside of the Loch Jetty was one of the best berths in the dock. Since No. 2 was reconstructed and a new solid structure put in its place, the inside of the Loch Jetty and the outside of No. 2 had become two of the worst berths."

Leigh favoured a breakwater extension to minimise the Run and pointed out the advantage of narrowing the entrance to restrict its entry. He agreed that Run was reflected from the Woodstock beach.

Capt. Coombes, Assistant Port Captain for 4½ years at Cape Town, considered Run from the north stronger than that from the Milnerton shore. He considered that Run would be less in a large southern basin than in the smaller Victoria Basin.

Capt. Jackson of the S.S. 'Gaika' made the interesting comment:

> "We know, of course, that at one or two berths at the present South Arm when a heavy south-easter is blowing, towards evening there is a big Run."

He could not say, however, whether Run was due to a long swell entering the bay.

Mr. Warington-Smyth, an experienced yachtsman of Table Bay, voiced the opinion that development of the harbour on the north side of Victoria Basin would be likely to yield more Run than on the south side. Capt. Chope of the S.S. 'Kenilworth Castle', with 34 years experience of Cape Town, opined that Run was caused by north-westerly gales.

Capt. Dent, for 10 years a pilot at the harbour, essayed perhaps the first attempt at explaining Range action:

> '" My experience,...is that the cause of the Run in the dock is that the breakwater is not of sufficient length. Our heaviest Runs are not during...winds. The Run is always forerunner of a gale which is working up to the southwards. I proved this current times without number when I first joined the Service.
>
> " I have lain on the north end of Robben Island and drifted without working the engines, and have come right across to Green Point up along shore, then round the breakwater.... I maintain in this Run that there is a continuous current coming along the shore..... I am of opinion that the current breaks itself into two portions, one going past the end of the South Arm Elbow and the other finding itsway into the harbour. There is a dead water off the Elbow itself."

Dent referred to the fact that vessels berthed outside the South Arm Elbow experienced an off-and-on movement of thumping quite independent of the fore-and-aft motion. He remarked on feeling a definite current round the breakwater when there was a Run on, and considered that currents were stronger than mentioned by Lacy Good in his report of 1895.

Capt. Storm, 5 years a pilot at Cape Town, also had views on the origin of Range, his feeling being that it was caused by current and sea being split by the Woodstock beach, the greater portion heading north along the Milnerton shore and the remainder curving towards the harbour (Fig. 2, 1895) where it was reflected from the south side of the breakwater into the Victoria Dock. Enlarging upon this, he said:

> "(Run) comes from the sea, from the outside. Many a time we have not seen any sign of wind, everything being quite smooth, but if we could get the meteorological conditions, say, about 50 miles off, we would find perhaps it was blowing a gale of wind and the sea was running in this direction, but it (the wind) expends itself before we get it, though there is a volume of water that the sea drives in"!.

In reply to questions about conditions inside the Victoria Dock Storm considered No. 6 quay (Fig. 3) safe, but the East Pier was subject to an inside run, in proof of which, he said, one ship berthed there broke all her moorings. It was nevertheless not so bad as at the Elbow, which he thought a very unsafe place. Referring to conditions in the anchorage, Storm commented on the fact that with ships at anchor one sometimes found a vessel heading into the wind but with her cable leading sternwards instead of to the fore as might be expected.

Capt. Short, a pilot for 10½ years at Cape Town, added to the general picture by saying:

> "The only way you can do away with the Run in the dock is to increase the area of water in the harbour, so that the amount of water that piles itself up in the bay will have a larger area to extend over and therefore be slower in its movements."

Short thus considered there would be less Run in a larger basin than in a smaller one and averred that lengthening the breakwater would further decrease the Run. Regarding conditions in the harbour he thought ships lay more comfortably than elsewhere at No. 6 Quay and inside of No. 2 Jetty. No. 6 Quay he considered the best in the dock, while East Pier was definitely better than the Elbow. Short agreed that the only thing to stop the Run was to extend the breakwater sufficiently to "restrict the quantity of water piled up in relation to the volume of water enclosed". Run would affect a large ship more than a light one, he asserted.

Capt. Hussey-Cooper of the S.S. 'Berrima' pointed out to the Committee that scend or Run at Melbourne was very much more serious than at Cape Town and attained to velocities of 7 knots.

Completing the evidence of nautical men, Capt. Tose of Messrs. Thesen & Co., Ltd., put in a plea for a scientific investigation of the Run.

Among those not directly connected with navigation who were consulted by the Committee was Mr. George Stewart, lecturer in Civil Engineering at the University of Cape Town. He gave his explanation of the phenomenon as:

> " The reason of Range is, of course, due to waves entering the harbour, but it is not always necessary for a gale to exist when Range action occurs. The Range waves may be caused by gale some considerable distance from the harbour. A long rolling swell, common to the Cape, at a distance from a harbour has an accumulative effect on Range action."

Answering a question from the Committee, Stewart agreed that Range would be due to rebound of the swells from the coast of Table Bay. As we have recorded in the Introduction Stewart stressed the desirability of a model investigation of the problem before any scheme were decided upon.

Finally Mr. Cochrane, Assistant Resident Engineer with 25 years experience at Cape Town alleged that:

> "The Run, as a run, is merely the alteration of levels, one bit of water trying to come to the level of another bit is more or less confined by a narrow entrance."

He too agreed that the Run would be lessened by an extension of the breakwater.

17. Interviews with Harbour Officials in January, 1942.

As we have recorded in the Introduction, the new Duncan Basin at the time of the Range crisis in 1940-42, had just been enclosed from the sea and was in process of being completed. The hoped-for immunity of the new basin to Range-action was not realised; instead the behaviour of several very large ships moored there gave cause for grave concern. In respect of what is set out hereafter, which will naturally invite comparison with the last Section, it is as well to note that in the intervening time since 1921, the breakwater had been extended by 1250 feet, while a South Basin (Fig. 2, 1933) was constructed and completed by 1932, only to give way in 1938 to the larger design of the Duncan Basin.

Interviews with the Harbour Engineer, Port Captain and Pilots and various other persons in January, 1942, served to corroborate the experiences of the previous generation.

Mr. Lankester, Harbour Engineer, revealed that Range could exist without any wind, but, in general, was only of a serious nature if the wind was bearing from the north-west. Run, he said, was nevertheless also occasionally a feature of the summer months. No well-defined currents existed in Table Bay although due to the prevailing winds of north-west in winter and south-east in summer, the beach near the root of the new Eastern Mole successively eroded in winter and silted in summer.

Capt. Short, who gave evidence before the 1921 Committee and was by this time promoted Port Captain, held that the Range phenomenon was fundamentally due to swell - often originating far out to sea - impinging on the breakwater and recoiling there, while the unretarded part of each roller continued its course towards the shore. Owing to this interruption, he maintained, a head of water was built up on the end of each roller after negotiating the breakwater and this of necessity travelled sideways and entered the mouth of the new basin.

In a conference of Pilots convened by the Port Captain, which included Capts. Reed, Tarpy, Dutton, Caubin and Summers, opinion seemed to be unanimous that Range usually set in after the wind had been blowing from the north and had then veered to north-west or slightly west of northwest: unless the wind veered to this quarter the Range was not appreciable. Nautical opinion was also unanimous in holding the new Eastern Mole responsible for the Range in the Duncan Basin (Fig. 4). No trouble, it was alleged, had been experienced in the 1932 South Basin. Capt. Short cited the case of a schooner which had been moored for two years on the east side of the South Arm, before the first south basin was enclosed by the random block mole (Fig. 2), without ever being subject to any danger from Range action.

Capt. Short was quite emphatic in saying that the phenomenon was no new one, because it had always existed throughout the 31 years of his experience: it had merely become more accentuated and troublesome since the completion of the Eastern Mole. He asserted that the building of the Eastern Mole had cut off the natural spending beach which had previously existed between the Adderley Street Pier and the Salt River Mouth (Fig. 2), and this had deprived the harbour of its natural shock-absorber against heavy seas. That seas had in fact been very turbulent outside the old random mole before the construction of the Duncan Basin was confirmed by Mr. Alma, Assistant Manager of the Hollandse Aanneeming Maatschapij, contractors for the dredging and rock-breaking operations in the harbour development scheme.

Mr. Alma was able to furnish interesting evidence of conditions far out in the bay during prevalence of heavy seas. This was procured on an occasion when a crane on the breakwater, then being constructed on the east side of Robben Island, had become endangered by high seas. A tug was commissioned to take him to the scene. The swell at the time was apparently coming in from the open ocean round the end of the breakwater and curving southwards, but farther out the swell was at right angles to their path to Robben Island (Fig. 9) and therefore coming from the south-west. Near the island the swell actually curved northwards and was met by a swell coming south from the north-east side of the island. This latter swell was particularly violent and was causing most of the damage in that area.

Capt. Short's view that Range was caused by wave propagation through the entrances of the basins was disputed by Commander Dean of the Seaward Defence Force. Run or Range, he affirmed, was definitely not a swell in the accepted sense of the word, but a decided movement of water to and fro through the basin entrances at velocities sometimes observed to be of the order of 3 or 4 knots.

Nautical opinion was generally in agreement as to the positions in the basins where Range action was usually worst. In the Victoria Basin it was often quite pronounced and was especially bad on the east side of No. 2 Jetty and along the Elbow: no trouble was experienced on the west side of Nol 2 Jetty. In the Duncan Basin it was considered that the combined effects of the incoming and shore-reflected swells impinged on the basin near berth H and rebounded again across to the stub-berths on the Eastern Mole. At the same time Range was particularly bad along C and D berths: movement at these berths tended to be fore-and-aft and at E and the stub berths off-and-on, while rise-and-fall could be as much as 4 feet near H berth. Greatest damage, it was said, was done at the stub-berths where the off-and-on movement was considerable and dangerous. Besides a definite transverse Range across the Duncan Basin there was, according to Capt. Short, an observable longitudinal effect.

18. Extracts from Port Records prior to 1942*.

The Range question was discussed at great length and with some piquancy in the official correspondence of the South African Railways and Harbours Administration, which led up to the decision to institute a model investigation. It is as well to realise that this arose as the result of convergent circumstances; first, the progress in construction of the Duncan Basin from its inception in 1938; second, the increasing strategic position of Cape Town as a haven for large ships in the 1940-42 Allied crisis of the Second World War; and finally, the advent of particularly severe

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* L.c. (ante p.23), [13].

storms in the period 1940-42. Fig. 10 depicts the progress made in successive years in the construction of the Duncan Basin from its inchoation and it will be understood from this that, as no specific complaints regarding Range had attended the completion of the old South Basin in 1932, there is little account of trouble in the annals before 1939.

Fig. 10 will make it clear too that by November, 1939, just after the outbreak of war, the Duncan Basin first became an entity, a large expanse of water sealed off from the bay and allowed respiration only through a 750 ft. wide channel. The choking effect of the old South Basin's random block mole had by this time been removed and the stage was set for the impending drama.

The trouble came early in the winter of 1940 (April 28/29), and Capt. Weller, the Port Captain, in commenting upon it, threw interesting sidelight on the efficacy of the longer breakwater in relation to Range in the Victoria Basin:

> "Experience has proved that the extension of the breakwater by 1249 ft. which was completed in September, 1932, made an improvement in the Victoria Basin. Before the extension it was often necessary to take vessels away from the quays into the bay as it was not possible to hold them alongside in bad weather owing to the Run. It seldom occurs today, which proves that conditions have improved, although on occasions ships still break adrift and tugs have to assist in keeping them alongside."

Weller suggested the possibility of extending the breakwater still further to improve the Range conditions in both basins in the new circumstances, but the Harbour Engineer (Mr. Lankester), commenting on this, questioned whether the desired objective would be obtained and advised that it would be better to gain more experience of the conditions.

After the 'Mauretania' incident (Section 6, p. 23), the Port Captain wrote:

> " After this experience I consider the money would be well spent in making a large scale model of Table Bay and Dock with adequate apparatus to create the conditions that prevail when a heavy ground-swell rolls into the Bay. It could then be definitely ascertained if the extension of the breakwater would be the only solution, or whether some other means might be employed of lessening the surge in the docks..."

In the same letter he says:

> " Before the construction of E berth, C and D berths were not as bad as they are today during Run conditions, but they were definitely the worst berths on the night in question".

The System Manager, Cape Town, in reply, pointed out that the end of the new Eastern Mole was purposely designed in such a way that the entrance width of 750 feet could be reduced if necessary at no great cost to cut out more of the disturbance from outside, and that this narrowing had now been authorised. The question of a model investigation, it was considered, should be left in abeyance meanwhile.

After a further bad bout of Range on July 24th, 1940, Port Captain Weller reiterated his request for a model study:

> " So many theories have been advanced as to the cause and also to the reduction of the Range in the Docks, that I consider the best method is to experiment with a model as previously suggested."

But there the matter stood until the fury of the 1941 storms brought it once more to a head.

On July 4th, 1941, the Harbour Engineer was requested by the Chief Civil Engineer, on the representations of the General Manager, to undertake some investigation of the conditions with particular reference to the meteorological circumstances and the measurement of Range. Owing to certain difficulties which will be discussed later, the Harbour Engineer's enquiry failed to elicit any information of practical value before the author became involved in the problem.

? in Cap. p 75

The 'Brittanic' mishap of September 3rd, 1941, led to lengthy correspondence in which Capt. Short, the new Port Captain made the following significant observations:

> "All vessels at the stub berths on the Eastern Mole carried away ropes....At all stub berths wooden floating fenders were smashed to destruction. The vessels at A, D and F berths caused no trouble. Although there was fierce Run in both Victoria and Alfred Dock entrances breakages of ropes were few in Victoria Basin....The large vessels at East Pier and No. 3-4 South Arm did not part a single rope
>
> "All this goes to prove that Run conditions at quay berths are very erratic, but .... it is evident that the stub berths are always effected by Run and can be considered the most unfavourable in the New Basin."

The Port Captain proceeded to advance the theory that the head of water built up behind a ship between the stub jetties (Fig. 4) caused her off-and-on movement. Said he:

> " It is my considered opinion, supported by my senior marine officers, that if the stub berths were made a continuous quay, the berths there would be considerably improved. This opinion is based on experience (of) vessels .... moored .... north of the stubs and close to the new dock entrance. .... The conditions on the (straight) quay south of the stubs is even more favourable."

Continuing, Capt. Short advanced further opinions on the origin of Range:

> "In connection with the cause of Run or Range in Table Bay Docks, my experience, extending from 1911 (prior to the extension of the Breakwater) leaves me in no doubt that the extension of the Breakwater did not in the least degree lessen the Run in the Victoria Basin and that the Run in the New Basin as it is today is considerabl worse than when the New Basin was enclosed on the southern and eastern sides by the Random Block Mole (since removed).
>
> " There is no doubt that the Run or Range in Table Bay Docks is caused by the scend of rollers into Table Bay, which are mainly due to north-westerly gales which frequently blow home during the winter season; there are also many occasions when rollers come into the Bay without the least warning and sometimes during the Summer Season. I have known instances when the western side of Robben Island up to well south of Whale Rock has been smothered with heavy south-west rollers, and on the Green Point side of Table Bay the beach has been quite smooth, but the Run in the Docks was very severe.
>
> " It is the general opinion that reduction of Run in the Docks can only be done by a considerable extension of the Breakwater....
>
> " It must be admitted that the past Winter season gales have been the worst within memory of many nautical officers; one, an ex-Port Captain, and Nautical Adviser, has assured me personally that it is the worst he has known for over 45 years...."

In a long letter of October 24th, 1941, the Port Captain replied to some arguments in which the Harbour Engineer had contested the former's theory of the action at the stub berths. The following extracts have a bearing on our subject:

> "From personal observations I am compelled to the belief that there is a larger amount of disturbance in the present New Basin than was in the Basin enclosed by the Random Block Mole, and for the following reasons:-
>
> (1) The eastern side of the Random Block Mole was constructed in a slight curve to the South-west which allowed a freer run for the wave action to expand on the beach from Woodstock around to the westward....
>
> (2) Most of the wave action entering the....enclosed basin was broken up in the irregular masses of blocks of the mole, and further, there was a large area of gradual shoaling water on the western side of the Basin which also had the same effect.
>
> "The New Basin is now enclosed with the Eastern Mole and the advantage of an extensive gradual shoaling water area....has been taken away, and with the greater portion of the New Basin enclosed by vertical quay walls which only deflect the wave disturbance.... without reducing it to any appreciable extent, it will be admitted that heavier wave action must be present in the New Basin.
>
> "It is also my opinion that there is a wave action which travels to the northward along the Eastern Mole and contributes a holding up force to the wave action which comes from the ends of the....rollers as they sweep past....the breakwater and causes a considerably greater disturbance to enter the New Basin than was the case when the south and west areas of the Bay were open as a wave trap."

Capt. Short concluded by advocating the construction of two short converging breakwaters on either side of the Duncan Basin entrance to afford greater protection to it from both the north and the east sides.

19. Other Sources of Enquiry.

The only other information on local conditions which could be garnered at this time was to be found in a paper written by Mr. George Stewart on 'Harbour Design with Special Reference to South African Conditions'*. Written in 1935, this is chiefly remarkable for the attention it draws to the importance of the Range problem at Cape Town.

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*L.c. (ante p. 5), [3].

Stewart's explanation of the phenomenon is less satisfactory and does not, in point of fact, establish what happens and why. He attributes Range action to waves entering a harbour as a result of local or distant storms and also 'wave accumulation due to physical and artificial characteristics'. The phenomenon is explained as a transmission of wave energy. Stewart supports the view held by many mariners at Cape Town that Range is influenced by wave reflection from the shoreline of the bay. He maintains, in respect of Table Bay Harbour, that Range is of no consequence when the wind bears from due north owing to the limited fetch of water in which waves can be generated.

20. Analysis of Views.

The digest of all the information presented in this chapter is contained in the Introduction and needs no recapitulation here. However, some more detailed analysis of particular aspects of opinions and impressions can be made with profit for later comparison with facts, for obviously the views of experienced mariners cannot be treated lightly and must be made to accord with the facts or otherwise be disqualified on the basis of false premises.

Concerning the origin of Range-action, it seems to be variously attributed to swell and ocean current, hounded into Table Bay by local or distant storms, the latter of which do not necessarily blow home to the port. Capts. Coombes, Dent and Storm (1921) attribute the Run to current, but they disagree as to its circulation and Capt. Storm, we suggest, was influenced in his opinion by his recollection of the relevant passages dealing with currents in the handbook, 'African Pilot' (Cf. Section 11). Stewart (1921 and 1935) ascribes Range-action to a transmission of wave energy resulting from penetration of swell into the harbour, (a somewhat intangible explanation) and from the rather nebulous alternative of 'wave accumulation due to physical and artificial characteristics', the meaning of which is apparently left to the imagination. Capt. Short (1921 and 1941-42) seems to have extended his views considerably on the nature of the Range phenomenon. His original supposition that Range would be reduced by the provision of a larger dock area over which to dissipate it, having proved wrong in the case of the Duncan Basin, is discarded in favour of a more practical thesis: closer observation seems to have led him to the belief that incoming swell, in combination with shore-reflected waves returning along the Eastern Mole, penetrates the harbour entrances and thence ricochets from wall to wall within the basins. Commander Dean (1942) disputes the conception of penetration of swell and is supported by Cochrane (1921) in attributing Range to the flux of water through the basin entrances, necessary to equalize disparities of sea level inside and outside the harbour. Capt. Weller (1940), in his plea for a model investigation, makes the significant suggestion that heavy ground-swells are responsible for the surges in the harbour basins. Stewart (1935) maintains that northerly gales are in general unable to promote the necessary conditions for Range, but Capt. Johnson (1921), supported unanimously by Capt. Short and his Pilots (1942), considers a north wind perhaps the most favourable pre-requisite for Range development.

Capts. Short and Weller (1940-41) express entirely contrary views regarding the efficacy of the 1932 breakwater extension towards improving Range conditions in the Victoria Basin. But on the question of the berths in the docks where Range is severe or otherwise, nautical men are in good agreement. Capts. Leigh, Storm and Short (1921) all concur in rating the Elbow and the East-side of No. 2 Jetty the worst berths in the Victoria Dock. The South Arm berths were considered bad, but No. 6 and 7 quays, the East Pier and the West-side of No. 2 Jetty good, with No. 6 the best. Obviously the relative susceptibilities of the berths to Range action could not have altered much with the construction of the Duncan Basin, since Capt. Short and his Pilots (1942) accord the berths much the same rating.

In the Duncan Basin, by common consent, the stub-berths are considered the worst, action there being off-and-on: elsewhere, C and D berths are bad, A and B perhaps not so bad, while E berth promotes off-and-on movement and H berth pronounced rise-and-fall.

PART II

OBSERVATION AND MEASUREMENT OF RANGE

" ....we may perceive that every enquiry into the intimate nature of a complex phenomenon branches out into as many different and distinct enquiries as there are simple or elementary phenomena into which it may be analysed; ...."

— Sir John Herschel
Discourse on the Study of
Natural Philosophy, (1851).

CHAPTER IV

THE ADOPTED TECHNIQUE OF OBSERVATION.

> "....we acquire information respecting the phenomenon itself, by observing those with which it is habitually associated, that may help us at length to its analysis."
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> —— Sir John Herschel,
> Discourse on the Study of
> Natural Philosophy, (1851).

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21. The Exploration of Tide and Weather Charts.

The author's first care in January, 1942, after securing the information recorded in Part I, was to know what the behaviour of the sea and weather had been on the occasions when Range action had been prevalent in 1941. The only sea records available were those of two fixed tide-gauges, one an old Lege clockwork model in the Alfred Basin, the other a modern Lea electrical gauge located between E and F berths in the Duncan Basin and operating remote-control tide-dial and autographic recorder in the Harbour Engineer's Office. Not immediately aware at that time of the existence of the Lea autographic recorder, the author confined his first investigations to the Lege tidal charts.

These tide-charts provided a continuous undamped profile of sea-level in the Alfred Basin and were chiefly remarkable for the incessant and often precisely regular fluctuations which quite obscured the mean sea-level. Over the monthly chart these fluctuations were observed to vary considerably, some days being relatively small and others of large proportions. When the magnitude of this embroidery was correlated with the occasions when the effects of Range had been damaging to fenders, ropes and shipping it was immediately apparent that the tide-gauge was faithfully recording the surges of water into the inner Alfred Basin. An example of the type of chart traced by the instrument during heavy Range is given in Fig. 11, the occasion being one of the worst incidences of Range within the history of the harbour, June 19th, 1942. The oscillations recorded are typical of the magnitudes and frequency of the rise-and-fall movement in the Alfred Basin, successive peaks or troughs occurring at approximately regular intervals of 5½ minutes.

As Fig. 4 will show, the Alfred Basin is the last link in what is virtually a chain of basins leading to the Victoria Dock entrance, all of which are well protected by the breakwater: in consequence very little of the high-frequency storm commotion ever penetrates within it. Were this otherwise, Fig. 11 would be a dense black band in which the pattern we have noted would be unrecognizable. The Lege tide-gauge is thus automatically damped against high-frequency disturbances and forms a useful index of slower mass-movements of water.

Use of this fact was made in attempting to align Range disturbances with meteorological conditions; for charts were at once compiled giving the maximum amplitude of oscillation (half-range) above or below mean tide-level at 6-hourly intervals throughout the winter months of 1941, together with the wind velocity and direction and the barometric pressure over the harbour area. Fig. 12, which shows the sequence, reveals that the Alfred Basin is never entirely free from this slow rhymtic breathing, even in the most clement weather. The periodicity of it varies either between 4 and 7 minutes, with an average of 5½ minutes, or between 10 and 12 minutes, with an average of 11 minutes, as may be seen from the chart. Sometimes the 11 min. periodicity seems to predominate almost to the complete exclusion of the 5½ min. one, but this, it will be observed, is generally in fine weather when wind velocities are low. On the whole the 5½ min. periodicity is more prevalent, especially during storm periods when the magnitude of the oscillation grows above its normal amplitude of about 4 ins. The fact that the two periodicities are related, one being double of the other, has a special significance into which we shall enquire later.

Reference to Fig. 12 will show that in general - but not always - deep breathing in the Alfred Basin (amplitudes above 10 ins.) is preceded by strong winds from the north-west. High winds from the south-east, such as occurred from August 18th to 21st, 1941, have no effect in increasing the oscillation. However, no hard and fast relation seems to exist between north-west winds of gale velocity and the incidence of pronounced movement in the Alfred Basin: a closer relationship would appear to involve barometric pressure, for amplitudes show a tendency to increase, with time lags, after atmospheric pressure has dropped below about 30 ins.

The discoveries enumerated above provided important clues to the unravelling of the whole mystery of the Range phenomenon at Cape Town, for in pondering this question of oscillations over-riding the main tidal wave in flood and recession, the author was minded to refer to Sir George Darwin's masterpiece on 'The Tides'*, which as we shall see in the next chapter, discusses closely-related phenomena.

In the hope that still closer relationships might be uncovered between weather conditions and Range, the author consulted Dr. Schumann, Chief Meteorologist, in Pretoria and was afforded the opportunity of studying meteorological surveys of the country for the period May to September, 1941. After close scrutiny and comparison with the curves of Fig. 12, it had to be admitted that no further light could be shed on the matter from that source. Dr. Schumann considered that a knowledge of meteorological conditions over the ocean to the west of Cape Town might yield some clues to the development of Range, but information concerning this area was not available in wartime. Later, as will be described, the author approached the Naval Meteorological Station, South Atlantic, and was able to follow up this avenue of investigation to some extent.

Compilation of the meteorological-tidal relationships was continued as a routine measure throughout the time that the author was investigating the Range problem, and is now still being maintained as a check on general conditions. Fig. 13 is representative of the correlation chart for the first part of the winter of 1942, a few months after the research was under way. Additional refinements were introduced in course of time, as may be judged from Figs. 14, 15 and 16. Air temperature and tidal range were included, together with the amplitudes and periodicities of the predominant oscillations recorded by the Lea tide-gauge in the Duncan Basin. Fig. 14 shows also relevant data for Port

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* L. c. (ante p. 38), [28], pp. 21-58.

Elizabeth superposed on the diagrams for Table Bay Harbour, to which reference will be made in due course.

22. Visual Observation of the Range Phenomenon.

It was very necessary to a full understanding of the Range phenomenon that the author himself should witness what transpired by direct observation on the spot. He was, however resident in Johannesburg, 1000 miles from the scene, and the difficulties of distance and of anticipation were considerable. Throughout the major portion of the winter of 1942 the author was obliged to shoulder the many duties of the Research Engineer in the latter's 3-month absence as Acting Inspecting Engineer, and it was not possible to be present at Cape Town for more than just a few days at a time. The best expedient that could be adopted in these circumstances was a standing arrangement with the Port Captain to phone or telegraph warning of the fall of the barometer below the 30" level--a direct product of the analysis of the 1941 tide and weather charts.

Unhappily, in the stress of war, the author was not permitted to fly to the Cape by plane and had necessarily to travel by train. The inevitable result was that, with any given warning, he invariably arrived on the scene too late to see more than just the sluggish aftermath of the Range occurrence. The incidence of May 19th, 1942, (Fig. 13) passed in this way and the author was still on the return journey by train to Johannesburg when the next big bout of May 24th took place.

The same thing happened on the occasion of June 19th (Figs. 11 and 13) when Range was very severe. According to accounts given by Capt. Short, Port Captain, and Mr. Read, Assistant Engineer, the Alfred Basin 'cut' or entrance was a veritable mill-race, with water rushing to-and-fro every 2 to 3 minutes at velocities approaching 10 to 12 knots. As Fig. 11 shows, just after 10.00 hours, the water level in the Alfred Basin fell 5'-2" in about 2¼ minutes, and in the next few minutes rose again to within a few inches of the previous level.

While this was happening there was corresponding movement through the entrance of the Victoria Basin, so violent that it tore from its mooring-buoy one end of the floating anti-submarine boom and carried the whole net bodily into the harbour. From then on the boom whipped in and out of the entrance with each surge of water, held only by the mooring at the Elbow. Mr. Jones, Draughtsman at the Harbour Engineer's Office, who superintended retrieving operations, recounts that the struggle to harness the free end of the boom continued all day and was not finally successful until the following morning. As may be supposed the operation was dangerous because vessels of any size were virtually powerless in the strong surges. Jones stated that the head of water, built up alternately outside and inside the entrance above the level on the other side, was clearly noticeable and of appreciable magnitude. The effect of this occurrence of Range upon shipping in the harbour has already been recorded in Section 6 (p.25) and need not be detailed again.

At this stage the author decided to wait in Cape Town for the next advent of Range, which came in moderate form on July 4th, 1942. This time the Lege tide-gauge in the Alfred Basin showed an overall rise-and-fall of 3 feet at the maximum with a period approximating 6 minutes. The flood of water through the 'out' was very pronounced with a maximum velocity of about 4 knots, reversing regularly about every 3 minutes. In the entrance of the Victoria Basin, as also that of the Duncan Basin, the flood and ebb of water was plainly discernible although velocities there could not have exceeded about 1 knot. In both these entrances the period of this recurring action was timed to be about 6 minutes. The harbour at this time was virtually empty of ships and no trouble was encountered. Apart from the water movement in the basin entrances there were no other visible effects of the Range alongside the quays other than the normal turbulence of choppy sea.

23. The Problem of Measuring Range-Action.

Even before the author had had the opportunity of seeing for himself the nature of the problem he had to contend with, he was faced with the urgent task of devising ways and means of measuring its effects in time for the winter of 1942. This problem had descended earlier, in 1941, upon the Harbour Engineer, as we have mentioned in Section 18 (p. 56), the Chief Civil Engineer having requested that officer*:

> "....to trace the direction and general influence of the disturbance outside the harbour together with its approximate period."

The instructions went on to say:

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*Letter of July 4, 1941, Official Papers W.904/180 of the Chief Civil Engineer, S.A.R. & H., Johannesburg.

> " The meteorological conditions prior to any such Run should be carefully examined to see if it is possible to predict the disturbances with any certainty.
>
> " Measurement of the Range must be made inside the new basin and in the old in order that its comparative extent may be known, and its velocity of propagation in the enclosed areas.
>
> " As it is impossible to obtain so many automatic recorders as will be required, simple enclosed apparatus should be erected at selected points in the old and new basin which can be visually observed. When a Run takes place observers could be stationed at these points and take the movement at synchronized times."

Some two months later the Harbour Engineer replied,* pointing out that it had not been possible to procure the services of a tug for tracing the disturbance outside the harbour, owing to the demands of shipping. A record of days on which Range had been prevalent was sent to the Meteorological Office at the Wingfield Aerodrome, Maitland (near Cape Town), but the report came back:

> "....we have examined our weather charts....the results have been negative."

The Harbour Engineer was fully alive to the difficulties of measuring the Range along the lines requested by the Chief Civil Engineer and concluded his letter:

> " The propagation of the Range in the basins is most irregular, being deflected from quaywall to quaywall and in consequence will be difficult to measure...."

There the matter seems to have ended, for the winter of 1941 passed away, and later correspondence from the General Manager impelled the Chief Civil Engineer to place the problem before the Research Engineer.

The task of how to obtain sufficient measurements of water movements within the basins of the harbour to show the simultaneous conditions prevailing over the areas, was indeed a difficult one. Two methods presented themselves: either a team of observers, equipped with synchronised watches, as

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*Letter of August 28, 1941, Harbour Engineer's Papers E.105/4.

originally suggested by the Chief Civil Engineer, would have to be employed, or automatic apparatus installed at selected points. The second method demanded precision instruments of which there was none in the country. All the known overseas types of automatic water-level recorders or tide-gauges were costly and of heavy design, demanding elaborate housings: in 1942, moreover, during the war they were not in production and would probably have been unobtainable in quantity, if at all. As against this was the fact, evinced from the study of the 1941 tide and weather charts (Fig. 12), that the Range phenomenon was associated with long-period movements of water, which human observers would be quite incapable of recording, since they would be almost wholly obscured by high-frequency wavelets, to which only the Alfred Basin was reasonably immune.

Obviously the problem could only be resolved by designing and manufacturing self-recording tide-gauges, properly damped to be insensitive to rapid changes of water level. The difficulties seemed overwhelming. Such few instrument-making firms as were then available in South Africa had no experience of tide-gauge apparatus: they were, in any case, geared to all-out war production. The detailed designing of a suitable instrument, ab initio, and the precision manufacturing of a number thereof, would have required months, even supposing the inexperienced designer could have evolved a perfect mechanical instrument from the start. In all these circumstances delays in reaching conditions of satisfactory operation could have retarded progress beyond reckoning, at a time when the beginning of the critical Range period of 1942 was barely 2 months ahead and the utmost urgency was attached to the collecting of data. In this quandary the author launched upon a bold yet simple idea: why not attempt the construction of a precision instrument from standard Meccano parts?

24. The Design of a Portable Seichometer*.

An experimental model was rapidly devised from private resources, the design taking root from pencil sketches (Figs. 17), and a satisfactorily sturdy, light-weight machine was evolved within only a few days. Powered with a synchronous, electric clock-motor, this machine successfully complied with all requirements in simple home-experiments.

Although the feasibility of this improvisation was early established in 1942, serious difficulties arose over the availability of materials, since South Africa was entirely dependent on pre-war stocks of all but essential war commodities. It was hoped that sufficient component parts could be secured for the construction of a dozen seichometers, but after enquiries in all the big centres of the Union it was found that there were barely sufficient for half that number of machines: nor was there any hope that they might be supplemented from imports, since the manufacturers had apparently ceased production. It was accordingly decided to construct only six machines. The Meccano agency in South Africa generously made available all its stocks of required parts, but in certain items the deficit had to be made good with substitutes manufactured in Railway workshops. While the search for materials was on it

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* The significance of this term will become apparent in the next chapter; the instrument has been so called for convenience, because designed to measure 'seiches' or sea oscillations.

looked as if the scheme might founder for want of synchronous motors, but these eventually were found.

The six machines were fabricated by Research staff within a month. Although only seven instruments were thus available (the author's model being included), their portability and interchangeability largely overcame the disadvantage of deficiency in numbers; features which were exploited to the full by designing some dozen-and-a-half pedestals and weather-tight housings for permanent attachment to the copings of the quay walls or jetties at the harbour (Fig. 18a). These fixtures were welded from sheet metal and scrap boiler tubes and were manufactured at the Rail Welding Depot at Elandsfontein.

As float chambers to contain the conical float and counterweight system shown in Fig. 17, steel pipes of 9-inch internal diameter and 5/8-inch thickness, varying in length from 30 to 50 feet were ordered from Messrs. Hume Steel (Pty) Ltd. of Germiston. Shorter 5 ft. lengths of 8 7/8-inch external diameter steel pipe, equipped with collars 6 ins. from one end so as to rest in the tops of the 9-inch pipes, were also procured. In the final assembly shown in Fig. 18a, these short lengths of pipe were intended as removable sections to facilitate dismantling at a later stage, and as wind-breakers to protect the float and counterweight cords.

Conical floats were designed to operate within the 9-inch pipes (Fig. 18b) and were shaped so that only a 1½-inch length would make contact with the inside of the pipes, when not otherwise riding free. The floats, together with block-lead weights were fabricated in Railway workshops, 12-gauge copper sheet being used for the floats in lieu of 14-gauge, which was unprocurable.

To provide the requisite damping of float movements, baffle-plates were attached to the under-water ends of the pipes. These plates carried a calculated number of perforations with the designed object of restricting float response to 20% of the external wave height for waves of 10 seconds periodicity, graduating to 100% for wave periods of 5 minutes and over. For pipes to be located inside the harbour basins 12 holes of 3/8-inch diameter were adopted; for pipes outside the harbour the number of holes was reduced to 8. A number of small holes was adopted in preference to a single large hole to discourage entry into the pipes of weed, barnacles, crustacea and other forms of sea life which might interfere with the float operation. The pipes were heavily coated with red lead primer and black bitumastic surface paints as preservatives.

25. Installation and Performance of the Seichometers.

The whole assembly of items - instruments, pipes, housings, floats, weights, sash-cords and electric fittings - was ready for installation towards the end of August, 1942, and full arrangements had been made with the Harbour Engineer for the erection of the material at the numbered locations shown in Fig. 4. After the strenuous efforts that had been made there was still good prospect that some of the seichometers would be in service before the end of the winter, but at this stage one of those extraordinary mishaps occurred for which it seems no allowance can ever be made. The pipes were duly delivered to Table Bay Harbour and off-loaded in an odd corner without any advice notes being delivered to the Harbour Engineer, who, quite unaware, continued to await their arrival. Having checked the despatch of the material from Johannesburg, the author meanwhile assumed that its arrival and erection would be automatic. This incredible situation was only discovered on September 22nd when the author expected to find the bulk of the work accomplished, and by then it was too late to complete things in readiness for the last visitation of severe Range action on October 8th and 9th. of that year.

This failure was naturally very disappointing at the time, but the consoling aspect, of course, was that in no other circumstances could measured data, additional to that of the two fixed tide-gauges, have been secured at all. What is more, it is almost certain that even had imported instruments become available under high priority, so dire was the strait of war at that time, there would have been little chance of their being in operation even in the following winter of 1943. Their cost, too, in quantity would have been fabulous in comparison with the seichometers developed, the actual cost of which was only £17 per instrument and £110 per float chamber and housing installed.

Figs. 19(a) and (b) are typical of the installations as finally made and show the seichometers in position. Photograph (a) is of station 11, (Fig. 4), and (b) is of station A at the centre of A berth, Duncan Basin, where the pedestal had to be cut away to avoid the fouling of running lines. Along the outside of the Eastern Mole the pipes were sunk through the interstices of the random block-work and were secured to the parapet wall. The station points (Fig.4) at which the housings were erected in the summer of 1942/43 were the best positions that could be selected in the face of the Port Captain's objections to anything fouling the quays: station 12 between berths B and C was only permitted by the Port Captain by way of trial. The pipe and housing at station 12 were finally wrecked by floating fenders and mooring ropes, and when later in 1946 at the request of the Chief Civil Engineer, installations were completed at A, C and E berths (Fig. 4), the pipes had to be recessed into the quay walling and the housings anchored down with substantial foundation bolts by way of protection, as shown in Fig.19(b).

The final test of the seichometers lay, of course, in their performance. Many refinements were introduced to the machines at different stages as will be evident from close study of Figs. 16 and 19. On the whole the instruments performed their functions well although a fair amount of trouble was experienced with the blocking of the baffle plates. Usually these had to be cleaned at the beginning of each winter season, a process which generally involved complete dismantling of the pedestals and pipes.

Owing to the transient and short-lived character of Range action it was the practice to install seichometers at selected observing stations only as occasion demanded, and to withdraw them from the housings immediately thereafter. Single sheets of paper attached to the drums of individual machines were well-suited to this discontinuous service and sufficed for securing records over periods of from 2 to 48 hours according to the gear ratios used. Chart paper was chemically sensitised with a deposit of zinc oxide and gave black traces under the impression of bronze stylus points.

A typical record during an incidence of Range is reproduced in Fig. 20 which shows the rise and fall of the sea outside the harbour near the root of the Eastern Mole, after high-frequency waves had been damped out of the picture. Further examples of seichograms will be considered in a later chapter.

26. The Measurement of Currents in the Harbour.

Before very much was known of the Range phenomenon it was considered necessary to determine current velocities at different depths of water in the entrances of the basins. An Ott suspended-rod type current-meter was procured for this purpose from the Irrigation Department in 1942 and was equipped with an automatic electrical recording system in Railway laboratories. After calibration of the instrument in the the hydraulic flume of the Witwatersrand University it was shipped down to Cape Town to await attachment to a suitable floating platform. Actually it was never used owing to the considerable difficulties of securing occupation of any basin entrance for a sufficient length of time to obtain representative measurements. Shipping activity at Cape Town in 1943 and 1944 was intense and the project was abandoned after further experience had indicated that current velocity data were anyway not essential to the research.

However, consideration was given at a later stage, in July, 1945, to the use of electrical pressure recorders and current meters for measuring the surges affecting ships at the quays and wave motion in the channel approaches to Table Bay. A successful type of instrument for this purpose was developed by Dr. Guelke, then Acting Head of the

Electrical Engineering Department, University of Cape Town, in collaboration with Commanders Goodlet and James of the Admiralty, and was in use on Robben Island during the war for the degaussing range established in the vicinity. It is unfortunate that the proposals to use this equipment, which became spare at the end of the war, were never implemented, but the occurrence of the 'Aquitania' incident forestalled them by compelling an all-out effort on model testing.

27. Aerial Photography of Wave Propagation in Table Bay.

Since Range, by all accounts, was intimately bound up with the penetration of swells into Table Bay it was held to be very desirable, as an aid to the projected model study, that something should be known of wave propagation in the bay. In 1942, therefore, negotiations were opened with the Department of Defence in Pretoria for enlisting its assistance in the aerial photography of Table Bay during an occurrence of Range action. Co-operation was forthcoming in generous measure and final working arrangements were completed with the Air Force Authorities at Cape Town when the author was transferred there in 1943.

Rather exacting conditions had to be met for successful photography: existence of a strong swell running into the bay was fundamental; prevalence of Range was desirable; absence of cloud near the sun was essential; and slanting sun's rays were necessary to set off the rollers in relief by their shadows. The first suitable occasion only came on September 15th, 1943, when the work was duly accomplished between the hours of 15.30 and 18.30. Photographs were taken at regular intervals from a height of 10,000 feet by a plane flying in a sequence of aerial lanes on a north-west course from the mainland.

The numbered photographs were lapped into strips corresponding to the air-lane along which the plane had flown. Some difficulty was found in overlapping correctly photographs which showed only areas of sea, but fortunately discolorations, foam-streaks and a few scattered ships allowed of an exact linking up. The strips were then connected transversely into four blocks each containing portions of land, and these were finally compounded into a single mosaic by adopting a system of triangulation, using the known distances from recognizable features on Robben Island and the mainland. The scale of the aerial photographs was established as 1 inch to 1960 feet and found to be very constant for each block of photographs, so that on this basis they could be correctly oriented and connected. War-time restrictions added to the difficulties of this work, for the Naval Censor insisted that all photographs incorporating the harbour area should be retained in his office. The author was obliged to compound the block of photographs retained by the censor at the Naval Intelligence Offices and prepare a tracing of the outline of the harbour and the wave directions for that block, in order to complete the general mosaic.

By superimposing upon the mosaic the co-ordinate network adopted for the design of the model, as will be explained later, the wave shadows could be drawn in on a similarly co-ordinated chart, yielding the results shown in Fig. 21.

The periodicity of the swell was measured by stop-watch at several points along the coastline and was found to be almost exactly, and very uniformly, 15 seconds. Very little of the swell was observed to curve round the breakwater owing to its south-west origin and the sea along the outside of the Eastern Mole was relatively quiet. Despite this, Range action in a mild form was prevalent in the harbour and Run at velocities of about 1 knot was observed in the basin entrances.

28. Measurement of Ship Movements.

The early studies described in Section 21 showed that surges of from 4 to 6 minutes periodicity were usually present in the harbour basins during Range action, and it was at first assumed that these must be responsible for ship vacillation. Observation, however, showed that ships were obviously influenced by more rapid perturbations than these and it became a matter of importance to isolate the critical disturbing factors. Range was notorious for being erratic in its action as Capt. Short's statement, quoted in Section 18 (p.57), bears out, and it became apparent eventually that the extent to which difficulties were experienced was dependent upon a combination of circumstances, particularly as regards the position of a ship, her size and displacement, her manner of mooring and the Range conditions prevailing. Results were often anomalous in that quite severe occurrences of Range produced little or no effect, and vice versa.

The first observations to correlate ship movement with Range action were made on July 12th, 1943, by noting relative degrees of tension in the stern mooring ropes of the 'Dominion Monarch' (34,000 tons displacement) at B berth, Duncan Dock, while a seichometer at station No. 12 alongside recorded the rise-and-fall of water between B and C berths. The results of this are shown in Fig. 22, the analysis of which we shall reserve for another chapter: it may, however, be noted in the interim that the ship was obviously responding to surges at intervals approximating 1½ minutes, and that a corresponding periodicity is apparent in the trace of water levels.

Fig. 23, which shows similar observations made almost a year later on July 19th, 1944, on a block-laying ship of about 10,000 tons displacement moored near seichometer station No. 18 along the Eastern Mole (Fig. 4), reveals that this vessel was clearly being influenced most by some periodicity of the order of 20 to 25 seconds, which, because of damping, is not evident in the seichogram trace. However, the occasional hesitation in the movement of the ship can be seen to correspond with the main water-level peaks which occur at periods approximating 3.8 minutes. Figs. 22 and 23 thus exemplify the differences in response to Range Action to which ships are subject.

Refinements in measuring technique were adopted in later observations of ship movements. Thus in August, 1944, the Port Captain was requested to connect the main mooring lines of the next large ship to be docked at A berth on to the 'Monarch' springs so that spring extensions under pull from the moorings could be correlated with water movements. As this could only be done at A berth, it became general practice thereafter to make simultaneous recordings of actual longitudinal and lateral ship displacements in relation to any particular quay. Two tapes were employed for this work, one being laid out along the edge of the quay, the other being stretched between a tie-point on the ship and the observer's hands. By keeping this second tape always at right angles to the first by moving along the quay with the ship, it was possible to read out the limits of displacement in the two directions while a recorder booked the figures and the corresponding times. Examples of these measurements will be considered later when the subject of ship motion is discussed in greater detail. The method, while admittedly subject to error, gave good results and dispensed with the necessity for any complicated self-recording device. No record was ever made of vertical ship displacement, this being considered of no particular importance to the investigation.

CHAPTER V

THE OSCILLATIONS OF THE SEA.

> "What are these oscillations (of the sea) with periods of 5, 10, 20 or 100 minutes, which are sometimes irregular? Are they analogous to our (lake) seiches? ....provisionally, I shall call them by the name of 'vibrations of the sea'. I venture to invite men of science who live on the sea coast to follow this study. It presents a fine subject for research, either in the interpretation of the phenomenon or in the establishment of the relations between these movements and meteorological conditions."
>
> — Dr. Forel,
> Seiches et Vibrations des Lacs
> et de la Mer, (1879).

29. Bibliographical Research into Range.

It was natural to suppose when this investigation began that the Range phenomenon at Cape Town was not unique and that it was probably common to a great many other ports of the world: it was therefore a basic aim of the research to find out what was known about Range in the literature of science and engineering. The persistence of the 5½ and 11 minute surges, discovered in the Alfred Basin as already narrated, coupled with the author's recollection of certain puzzling irregularities in the tidal charts of Port Elizabeth, seen long before in 1932, led him to enquire first whether there was any tidal origin for these parasitic oscillations of the sea. The first source of information was Darwin's work on 'The Tides' in which is unfolded the beautiful story of Dr. Forel's pioneering studies on the Swiss lakes which disseminated world-wide investigations of kindred lake and coastal phenomena. For a full understanding of the Range problem it will be necessary to recount some of this story, and a great deal more of the findings from various avenues of enquiry to which it was the introduction.

30. The Phenomenon of Lake Seiches.

It has been known for centuries that the water of Lake Geneva at its crescent-shaped terminals rises and falls on occasion, sometimes through a range of 5 or 6 feet at the long, funnel-shaped end of Geneva. That this variation was rhymthic in character first seems to have been recorded by de Duillier, a Swiss engineer, in 1730, who mentions that in his time the movements were known as 'seiches'. These oscillations were not merely confined to Lake Leman (Geneva) but were common to all lakes, as was pointed out by Vaucher in a memoir of 1803, in which he remarked that their occurrence seemed to be related to the condition of the atmosphere. These facts are recorded by Dr. Forel[*], the first person to conduct any scientific study of the phenomena, for which he has been called the 'Faraday of Seiches'[†].

Forel commenced his patient observations in 1869 at the harbour of Morges on the Lake of Geneva, using first of all a simple portable instrument called a plemyrameter, which enabled him to detect the rise-and-fall of the pulse-like movement of water. Later he developed a self-registering limnograph with which more factual data were recorded. By 1875 he was ready to show that the waters of Lake Leman rocked from end to end in a gigantic mass-movement, of which he exclaims ecstatically[§]:

> "....I feel bound to recognise in the phenomenon of seiches the grandest oscillatory movement which man can study on the face of our globe."

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[*] 'Le Leman, Monographie Limnologique'; (Lausanne), 1895,[40].

[†] By Prof. Chrystal: 'On the Hydrodynamical Theory of Seiches'; Trans. Roy.Soc.Edinb.,Vol.41,1904-5,Part III,[41],p.599.

[§] 'Les Seiches, Vagues d'oscillation', p.11; (cf. Darwin; lc.ante p.38, [28],p.28.)

When it is appreciated that the lake of Geneva is some 45 miles long by 10 miles wide near its centre, the significance of a movement in which every particle of water oscillates in perfect synchronism with every other may perhaps be realised. Forel recognised further that the seiche phenomenon in its most elementary form was due, in effect, to two waves, each of a length between crests of twice the length of the lake, travelling simultaneously in opposite directions to each other. The resultant of two such waves is a 'standing' wave with the peculiarity that it remains fixed in position while still performing the up-and-down movements characteristic of a wave. This standing wave in the case of the fundamental oscillation in a lake, amounts to an up-and-down movement of water at each end of the lake such that while the water ebbs at one end it floods at the other. Approximately half-way between these extremes the lake-level remains unaltered throughout the full cycle of events while the ends see-saw up and down. The line across the width of the lake at which vertical movements of water are nil is called a <u>node</u>, and the seiche itself is <u>uni-nodal</u> through having but one node in the length of the lake.

Forel soon discovered that there were bi-nodal, tri-nodal and other multi-nodal seiches existent usually at the same time. These latter seiches are higher harmonics of the fundamental seiche and are characterized by the fact that their periods are very closely integral submultiples of the period of the fundamental uni-nodal seiche. In addition to this Forel was able to identify the co-existence of systems of longitudinal and transverse seiches.

Forel's discoveries were taken up by numerous followers all over the world, such names as Plantamour, Sarasin, von Cholnoky, Delebecque, du Boys, Lauriol, Gautier and Endrös in Europe, Perkins, Denison, Bell, Dawson and Wheeler in America, and Airy in Britain being connected with the subject in the last quarter of the century. Intensive studies were pursued in the first decade of the present century, but Chrystal and his associates Murray, White, Watson and Wedderburn in Britain probably accomplished more than any others towards investigating the dynamical theory underlying the phenonemon and explaining its causation.

31. The Causes of Seiches in Lakes.

Forel himself was disposed to attribute the development of seiches to various causes such as that of a steady wind heaping the water towards one end of a lake and suddenly ceasing[*], of variations of barometric pressure overlying a lake, of possible disturbances to a lake bed from earth-tremor sources, but, most frequently and likely, of sudden storms or squalls traversing a lake.

As more evidence was amassed it became evident that small fluctuations of barometric pressure were much more important than would have been thought possible: Professor Chrystal in fact established that not only were minute variations of atmospheric pressure existent at the same time as seiches, but that mathematically they could be held to account for the phenomena observed. In his own words[†]:

> "Forel and his followers du Boys, von Cholnoky, and others have discussed the causes of seiches; and recently Endrös, in his important memoir on the Chiemsee, has confirmed the conclusions of his predecessors, and added some fresh details of great interest. In what follows we shall not advance anything of great novelty; but there are two points of interest which may be worthy of the reader's notice. In the first place the use of the Dines-Shaw microbarograph enabled us to follow continuously the minute variations of the atmospheric pressure with an ease and certainty hitherto unattainable. Also in an appendix to this memoir the mathematical theory of the effect of pressure disturbances

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[†] Chrystal: 'Investigation of the Seiches of Loch Earn'; Trans. Roy. Soc. Edinb., Vol. 46, Part III, 1908-9, [42], pp. 455-517.

[*] A clear case of this kind was recorded on Conowingo Pond on the Susquehanna River in Maryland, U.S.A., by R.E. Turner; cf. 'Operation of the Conowingo Hydroelectric Plant', Proc. ASCE., Nov., 1947, [126], p. 1373.

> of various kinds on an ideal lake, of form not very remote from Earn, has been worked out so as to show that the usually assigned cause of seiches, viz., the minor local fluctuations of barometric pressure, is in reality sufficient to cause the disturbances observed and is not a negligible quantity on ordinary lakes such as the tidal action of the moon can be shown to be."

Further on he says:

> " Observers are now agreed that the development of seiches usually accompanies local disturbances of the barometric pressure, whose duration if they are transitory, or period if they are periodic, does not differ greatly from the period of the seiche in question. Our observations on Earn bear out this conclusion."

Professor Chrystal in the course of this paper gives many examples of limnograms and microbarograms in testimony of this, of which Fig. 24 is a typical reproduction.

In a critical discussion of all the factors likely to give rise to seiches, Chrystal remarks that they may be sudden or gradual. Sudden generation could be the result of

(1) rapid release of pressure following upon progression of an isobaric system;
(2) sudden release of pent-up water at one end of the lake through lapse of the wind;
(3) heavy rain, snow or hail over portion of the lake;
(4) rapid change of air pressure through passage of a squall;
(5) flood discharge from rivers at one end of the lake;
(6) impacts of wind gusts on the lake surface:

whereas gradual generation could be occasioned by

(7) passage of small barometric fluctuations synchronising approximately with seiche periods;
(8) variations in wind velocity and pressure synchronising closely with seiche periods.

On theoretical grounds Chrystal disposes of factor (1) as being unable to explain ordinary seiches. Factor (2) he accepts if the thesis can be established that water is piled up by the wind: variation of pressure and rain usually accompany wind and it may be hard to discriminate on this point. Factors (3), (4) and (5) are all accepted as causes which can be adduced from observed results. Item (6) he finds hard to prove or disprove, but in its related form (8) it could certainly be a cause. Factor (7), however, he is able to illustrate as being a frequent and obvious stimulant in the production of seiches, and Fig. 24 provides a case in point.

As Chrystal's work is in large measure a summing up of all the evidence extant at the time, including his own extensive observations and measurements, we may reasonably accept his conclusions, already quoted (p. 87), as being the correct explanation of the seiche phenomenon in the great majority of cases.

Professor Chrystal, however, makes no mention in this discussion of causative factors, of the possibility of seismic origins for seiches, although in an earlier paper[*] he cites the fact that on the occasion of the great earthquake at Lisbon, on November 1st, 1755, remarkable seiches developed in Loch Lomond, Loch Lung, Loch Keatrin and Loch Ness, according to descriptions in the Scot's Magazine of that year. The author has discovered further fascinating accounts of similar repercussions in England and Europe recorded in the Gentleman's Magazine for 1755[†], which have a bearing on this question.

Although it is difficult at this time to know where the epicentre of that earthquake was, we must presume that it was within the vicinity of Lisbon, probably near St. Ubes (Setubal), for the captain of a Dutch vessel saw the mountain about 6 or 7 leagues from St. Ubes rend and fall into the sea at 9.45 a.m. The great catastrophe at Lisbon is variously reported as having occurred at about 9.30, 9.57 and 9.50 a.m., but at Cadiz, 200 miles distant, the shock was felt at about 9.56, and at Oporto, 190 miles away, at about 9.40 a.m. The earthquake was felt in Madrid at 10.20 (315 miles distant) and at Gibraltar at 10.10 a.m. (265 miles away). At Cork, in Ireland, shocks were felt at 9.30 a.m., and reports indicate that the earthquake was

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[*] L.c. (ante p.84),[41],p.599.
[†] L.c. (ante p.32),[23],pp.541, 554-564, 587-594.

felt in Milan and Scandanavia. According to Professor Chrystal the Scot's Magazine records that the seiches in the Scottish lakes developed between 9.30 and 10.15 a.m. and at Loch Lomond a rumbling sound was heard which suggests that the highlands received a full tremor. If we allow for the confusion prevailing at the time and the fact that shocks are reported to have lasted from 10 to 15 minutes at first, although they were repeated later in the day, we may consider the earthquake to have occurred at about 9.45 a.m.

Since earthquake waves travel with incredible speed, at an average perhaps of 20,000 mph* in the crustal regions of the earth, it would have taken only a few minutes for the disturbance to make itself felt in the Scottish highlands and it is a reasonable deduction therefore that the loch seiches were genuinely caused by the vibration of the lake-beds.

But in the low-lands of England and Europe seiches also developed in large ponds, canals and enclosed waters without any vibration of the earth being perceptible, and as their times of occurrence were much later than would be in keeping with shock-transmission through the earth, we are led to enquire whether their origin can be ascribed to pressure-waves in the atmosphere. The noise of the earthquake at Lisbon and the several accounts given of the earth opening and emitting clouds of smoke, dust and fumes would explain the creation of air-waves†, but proof positive of their existence in great strength is afforded by the following account from a correspondent in Leyden (Nov. 4, 1755):

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* Cf. Macelwane: 'The Interior of the Earth'; American Scientist, Vol. 34, 1946, [43], p. 196.

† Cf. also Milne: Earthquakes, (London), 1913, [44], Chapter IX.

> "On Saturday last, in the forenoon, the water in the several rivers, canals, and lakes, was agitated to such a violent degree, that at Woubrugge, Alphen, Boshoop, and Rotterdam, buoys were broken from their chains, large vessels snapped their cables, smaller ones were thrown out of the water on the land, and others lying on the land were set afloat. In the lake of Harlem particularly, the course of a vessel on full sail was suddenly suspended and the rudder unhung. No motion on land, of the houses and buildings was felt. During the time of this agitation, which continued near four minutes, not only the water in the rivers and lakes, but also all manner of fluids in smaller quantities, as in coolers, tubs, backs, etc., was equally agitated, and dashed over the sides, notwithstanding no motion was perceptible in the containing vessels. In such small quantities also, the surface of the water had apparently a direct ascent, prior to its turbulent motion, and, in many places, even the rivers and canals rose 12 inches perpendicular. It is asserted also from Amsterdam, that, *during this interval, the mercury in the barometer, which about this time was uncommonly high, descended instantly near two inches, and made several consequent vibrations.*
>
> (author's italics)

It is quite obvious that nothing but a series of air pressure-waves could have caused the barometer to have behaved in this fashion, and their existence at once explains the seiche-phenomena described, in terms of Professor Chrystal's findings on fluctuations of barometric pressure. Further confirmation of the seiche-like behaviour of enclosed waters is given in a letter from Amsterdam (Nov. 7, 1755):

> "The late extraordinary agitation of the water extended beyond Utrecht, and also southward to Brabant; where in the district of Hertogenbosch, it lasted near half an hour, occasioning wrecks of vessels, long since sunk, to rise to the surface and float for several minutes, notwithstanding there was not the least wind, nor any motion discovered in the land.
>
> "At Lubeck in Holstein, the water in the Trave rose four or five feet perpendicular in an instant, by which motion the ship of Capt. Panders snapped its cables, and great damage was done to other vessels. The agitation of the waters is said to have lasted nine minutes; and it appears everywhere, indeed, to have lasted proportionable to the height of the instantaneous ascent. From Gluckstad and other places there are also similar accounts, all agreeing that not the least motion was observable on the land.
>
> "And letters from Brussels mention that it was felt very sensibly through the whole course of the rivers Weser and Elbe."

Additional evidence for an air-pressure origin of these remarkable occurrences is furnished by accounts of what took place in England. A letter from Portsmouth, dated Nov. 3, 1755, says:

> " On Saturday last (Nov. 1st) his majesty's ship Golport was carried into the dock to be cleaned; about half an hour past ten in the morning she was observed to pitch forward with her head deep in the water and immediately to recover it and pitch as deep in with her stern; the water about her was greatly agitated, and the dock gates forced open about six inches.
>
> "At a very considerable distance is a large basin, which has not the least communication with this dock, and in it are the Berwick, Nassau, Dover, and another large ship; these at the same instant felt the shock, but instead of pitching they rolled very violently; none of those who were on the land could perceive the earth either under or about them to move."

The direct distance from Lisbon to Portsmouth along a great circle is about 975 miles, and if the air waves are presumed to have travelled at 780 mph*, they would have passed over Portsmouth about 1¼ hours after occurrence of the earthquake, that is, at about 11.0 a.m., which within the limits of error is in good agreement with the time of the incident quoted above. At Cranbrook, Horsmanden and Tenterden in Kent, some 20 to 30 miles north of Portsmouth, agitation of water in dams and ponds is described as having occurred between 10 and 11 in the morning in similar circumstances; while at Finchingfield, Essex, and Barlborough, Derby, respectively 1075 and 1145 miles from Lisbon as the crow flies, seiches in ponds are recorded as having occurred between 11 and 12 a.m. Over these greater distances, in the latter two instances, the air waves would have taken respectively 1.38 and 1.47 hours, making the times of arrival 11.08 and 11.13 a.m., which again are seen to be in good agreement with the observations. Had these disturbances been caused by direct earth-tremors they would have developed between 9.30 and 10.0 a.m. as did the seiches in the Scottish lochs and it is almost certain that ground vibration would have been felt. The remarkable circumstance that the terrestrial shock-waves penetrated into the highlands over a wide field, but failed to disturb the intervening lowlands is a problem we must leave for the geo-

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* This is the theoretical speed of sound in air at 80°F.

physicists, but, on the evidence, the author is impelled to the conclusion that concussion-waves in the atmosphere arising from the great earthquake must have been of a periodicity sufficiently close to the seiche-periods of a large number of bodies of water to impress upon them the extraordinary oscillations described.

32. The Significance of Lake Vibrations.

Besides the regular lake seiches, Forel recognized more rapid oscillations with periods of only a few minutes which he called 'vibrations'. These he noticed arose when the wind blew from certain quarters, but whereas the visible wind waves had periods of only 4 to 5 seconds, the vibrations usually had periods of from 45 seconds to 4 minutes. Forel came to the conclusion eventually that these vibrations were longitudinal seiches of high nodality; higher harmonics, in other words, of the more fundamental seiches, but Professor Chrystal, discussing this question, points out that all the evidence is against such an hypothesis. Chrystal found the same embroidery of vibrations on his limnograms for Loch Earn with periods most frequently of the order of 1.5 minutes. It was never observed unless there had been sufficient wind to generate ordinary surface waves, and it subsided with the disappearance of these waves: further it was usually a feature of the leeward or receiving end of the lake but absent at the windward end. In most cases too the microbarograms showed what Chrystal calls 'wind-blurring', suggestive of fluctuations of very short period, which in some cases seemed to coincide with the lake vibrations, but Chrystal was unable to establish any direct association with fluctuations of wind because of the condensed time scale on the anemograms.

If the vibrations were, in fact, high-nodality seiches, then their phases at opposite sides of the lake must be the same, but by signalling he was able to disprove this.

Forel noticed that the steamers on the Lake of Geneva generated vibrations very similar to the wind's, and the embroidery from the latter, because of this, could only be studied at night when steamers were not plying to and fro. The remarkable thing about the steamer vibrations was that they preceded a vessel so that it was possible to be aware of its approach as much as half-an-hour before its final arrival at the observing station. This peculiarity of antecedent vibrations was noticed also by Chrystal in respect of the approach of a squall, and he likened the phenomenon to the well-known fact of a swell presaging a storm at sea.

Professor Chrystal reached no final conclusion on the enigma of the lake vibrations unless it was that changing wind pressure would generate trains of waves of differing wave-length, which as wave groups might account for some of the periods in the embroidery. Sir George Darwin, while expressing considerable surprise at the fact that waves of a length between crests of from ½ to 1 mile could be generated by wind and steamers, was disposed to explain their existence on the basis of the analogy of the waves created by a stone falling into water. Waves so generated are of all wave-lengths, but it is the longer ones which out-distance and precede the shorter ones. Darwin, however, remained mystified as to what governed the length of the waves and why in the vibrations there was such complete separation between the long and the short waves.

33. Sea-oscillations of Seismic Origin.

Long before Forel commenced his researches on seiches in lakes, it had been a matter of common observation that bays and estuaries fronting on the sea were sometimes subjected to extraordinary convulsions from huge waves. In a small way these conditions were no different from the great tidal waves (the true tides) that sweep up many coastal inlets such as the Bay of Fundy, the Severn Estuary, and Hangchow Bay, to mention but a few, but because they were unusual and unexpected they were always dangerous.

The great earthquake of Lisbon generated big sea-waves of this kind, and as their effects were peculiar to many of the harbours which they overwhelmed, it is of some interest to our argument to consider the various accounts of them given in the Gentleman's Magazine of 1755, to which reference has already been made.

Lisbon lies on the north bank of the considerable estuary of the river Tajo (Tagus), which with its comparatively narrow mouth is virtually an enclosed piece of water. Into this rushed the sea-waves that followed sometime after the earthquake and

> "....whilst the multitude were gathered near the riverside, the water rose to such a height that it overcame and overflowed the lower part of the city,...."

This is the account of a captain of a British vessel, which was anchored in the estuary, who had previously felt the earthquake itself as a shock suggestive of the ship having fouled the river bottom. He records further:

> " ....boats were carried away by the retiring sea, which ebbed and flowed, ebbed and flowed in four or five minutes,....and the tide so quick eastward and westward, that the ships turning fast round, ran foul of each other.....I observed the Sea at the Bar break feather white as if agitated by a storm.....By my best judgment the water rose in five minutes about 16 feet, and fell in the same time for three times, and at two the tide returned to its natural course."

All this suggests that the sea-waves had a period approximating 10 minutes, although another eye-witness on the land said:

> " But this dismal earthquake had such an influence upon the sea and river, that the water rose, in about ten minutes, several yards perpendicular;...."

The sea-waves bore down upon Porto, Cadiz and Gibraltar and indeed upon the whole coastline in the neighbourhood. A correspondent writing from Porto records that the earthquake shock was felt at about 20 minutes before ten in the morning. Only a few minutes before starting his letter he mentions that another concussion was felt at 11.20 a.m. Obviously at that time the sea-waves had not arrived, for he says:

> " The ship this goes by sails tomorrow morning, so shall defer concluding till near the time she sails."

He continued his letter at about 4.0 a.m. the following morning, and recounts that a further shock was felt at about noon, to which he apparently ascribes the remarkable effects on the river:

> "....the tide rose considerably higher than was ever known, except in case of a flood; and the flux and reflux was so sudden, that in a minute or two it rose and fell five or six feet, and continued so for two or three hours; this I was witness to."

In reality, of course, this commotion was being caused by the arrival of the sea-waves generated at 9.45 a.m. by the main earthquake disturbance.

At Cadiz the earthquake was also felt at about 9.45 a.m., but according to another correspondent,

> " An hour afterwards the sea was calm, not a breath of air, but prodigious close and warm; on a sudden the sea swell'd up (without the least wind) all round the city;...."

Similar effects were felt at Gibraltar, where:

> " The sea rose six feet every 15 minutes, and fell so low that boats... were left aground.... This flux and reflux lasted till next morning, having decreased gradually from two in the afternoon."

The seismic sea-waves, fanning out from their epicentric origin, raced towards the southern coasts of Ireland and England. At Kinsale, in Ireland, it was reported on the day of the earthquake that

> "....in the afternoon, when the tide had ebbed some time, it suddenly returned with a violence and impetuosity impossible to describe..... These sudden and surprising fluxes and refluxes of the sea continued from three in the afternoon till ten at night, seldom more than a quarter of an hour between each return."

From Swansea, Wales, came another report to the effect that on

> "The 1st inst. about three quarters past six in the evening, a mile and a half up the river, after two hours ebb, a large head of water rushed up with a great noise,.... It fell almost as suddenly, for in 10 minutes there was no appearance left of more water than usual at that time of tide..... A vessel arrived since from Hayl in Cornwall brings an account, that the same day, about four in the afternoon, they had three heads of water, one after the other;...."

From these accounts and the knowledge we now possess of the speeds of long waves in different depths of water, it is certain that these various effects had a common origin at the time and place of the great earthquake, probably close to Setubal on the submarine escarpment that connects with the island of Madeira*. It is significant that off Cornwall three 'heads' of water were experienced, agreeing precisely with the three main waves reported in the estuary of Lisbon itself. Only one head of water rushed up the Neath river at Swansea, and presumably this is because the waves merged in the shoaling waters of that estuary. It is worthy of note that at both Kinsale and Gibraltar the periodicity of the waves was 15 minutes, and at Lisbon 10 minutes, while at Cadiz it would seem to have been about 5 minutes. These differences are not impossible owing to a certain amount of occlusion of the main periodicities from seiche-like effects peculiar to the bays and estuaries where the observations were made.

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* The author has checked this by calculation, using equation (8), Chapter VI (post.).

An important point that arises from the examination of this case is that the disturbances in the various bays and inlets continued for long hours after the arrival of the seismic sea-waves, and while the reason for this could possibly in this instance be imputed to subsequent minor shocks, we shall advance the suggestion, on the basis of further evidence to be revealed in due course, that the explanation for it is to be found in the pseudo-seiches which were created by trains of following waves and by the initial disturbances themselves.

There have been many earthquakes in history which have produced seismic sea-waves of great destructive power, but probably none so widespread in its effects as the great eruption of Krakatoa in 1883, which saw the virtual disappearance of that island in the Sunda Strait between Java and Sumatra. Inasmuch as the sea-waves from this gigantic molar disturbance penetrated Table Bay and scores of other bays and harbours as far afield as the North Atlantic and the Eastern Pacific, consideration of their effects has special interest and local flavour for our theme.

The great sea-waves which were generated by the convulsions of Krakatoa were some 60 feet high at their origin and had a periodicity of approximately two hours with a distance between crests of the order of 80 miles*. Their progression through the Sunda strait on August 26th and 27th, 1883, seems to have induced second harmonics, with the result that the waves were propagated across the oceans at intervals of about an hour apart. Wave-trains of shorter periodicities were observed by various witnesses so that it is probable that a rather mixed assortment emanated from the disturbance.

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* Cf. Report of the Krakatoa Committee of the Royal Society, (London), 1888, [45].

These wave-trains produced remarkable embroideries on the marigrams of tide-gauges at Colombo, Vizagapatam, Ceylon, Mauritius, Port Elizabeth, Cape Town, Honolulu, San Francisco and many other ports, but the significant thing is that the prominent periodicities which were excited in these harbours were often widely different. At Mauritius, for instance, the main periodicity was between 30 and 40 minutes, whereas at Mahe, in the Seychelles, it was 21 minutes; at Honolulu the period was 30 minutes, while in San Francisco Bay the conspicuous periods were 24, 34 and 47 minutes.

The disturbances reached Table Bay some 14 to 15 hours after the final paroxysm of Krakatoa and revealed themselves as undulations about 18 inches high and of about 62 minutes period with overlying oscillations of about 10 minutes periodicity. The marigram for Cape Town is a poor record unfortunately and more precise identification of periodicities is difficult. We should note in passing that in 1883 the harbour was not greatly different from the configuration of 1877, shown in Fig. 2, a circumstance which we believe has significance in respect of the 10 minute vibrations apparent at this time, as will be commented upon later.

At Port Alfred and Port Elizabeth oscillations of from 10 to 20 minutes were particularly pronounced. The 'Harwarden Castle' mail steamer which was anchored in Algoa Bay at the time of the arrival of the seismic sea-waves was swung about her moorings with such force that the friction-brake by which the cable was held, slipped, and it became necessary to drop another anchor.

Here the evidence is manifold that the various gulfs, bays and armlets of the sea were responding mostly to particular frequencies of waves which corresponded to their natural shape and depth. As with the Lisbon earthquake the vibrations continued for hours and even days after their commencement.

The explosion of Krakatoa also gave rise to a series of huge air-waves which expanded in concentric circles round the atmospheric envelope of the globe to condense at the antipodes, diametrically opposite from Krakatoa, and thence to oscillate backwards and forwards no less than seven times between these focal points. The air waves were registered on barographs all over the world as an initial depression followed by a sudden rise: their speed was found to be between 674 and 726 mph according to the direction in which the waves were travelling, being influenced by an average westerly air-current of 14 mph. With the same thought in mind of the effects which the air-waves from the Lisbon earthquake had upon the ponds and canals of England and Europe (Section 31), the author was led to enquire whether the Krakatoa air-waves could not have been responsible for similar effects at Cape Town and Port Elizabeth in the respective bays. Owing to the far greater speeds of air-waves over sea-waves, any manifestation of sea-oscillations engendered by air waves should be revealed in the marigrams long before the arrival of the sea disturbances. An inspection of the records for Cape Town and Port Elizabeth at the times of crossing of the air-waves failed, however, to reveal any measurable effects that could be associated with them. On referring now to his notes of this phase of investigation, the author notices that Capt. Wharton, who compiled the memoir on the sea-waves for the Committee of the Royal Society, was much puzzled by the fact that considerable short period oscillations at Port Alfred preceded the main waves. It is just possible that seiches may have been excited in the estuarine waters of that small harbour by the air-waves, but at this time of writing the author has not the facility for referring again to the Royal Society Report to check the possibility.

One further example of seismic sea-waves may be considered as having the special value of recency in our time: this arose on April 1st, 1946, from a submarine earthquake whose epicentre was in 9000 feet of water at 163°W long., 53½°N lat. in the Aleutian Trench. The waves were recorded on arrival at 15 tide-stations of the United States Coast and Geodetic Survey, and at points on the coasts of British Columbia, Costa Rica, Peru and Chile. A full report of this interesting occurrence has been prepared by the United States Coast and Geodetic Survey* from which we reproduce in Fig. 25 a typical marigram for Clayoquot, British Columbia, illustrating very clearly the sudden arrival of the forced waves and the development thereafter of parasitic oscillations, attenuating slowly over a long period.

It was found from the many such records that the average periodicity of the sea-waves was 15.6 minutes, a value which lends some credence to the belief that the Lisbon earthquake must have generated very similar waves. The marigrams reproduced in this report leave no doubt of the fact that bays and inlets of the sea are subject to the same kind of oscillations as inland lakes and that seismic sea-waves are at least one cause of excitation.

34. Coastal Seiches of Meteorological Origin.

If seismic sea-waves are responsible for the most spectacular and cataclysmic effects along the coastlines of the world,

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* Green: 'Seismic Sea Wave of April 1, 1946, as Recorded on Tide Gages', United States Coast & Geodetic Survey, San Francisco, California, [46].

they are certainly not the most frequent: hurricanes and cyclones are a far more prolific source of devastating seas, and very often they give rise to a mass-transport of water through combination of intense wind and barometric suction. For the present, however, we shall defer consideration of these exceptionally violent effects to discuss more fully the phenomenon of coastal seiches.

The sea-oscillations we have noted as occurring in bays and inlets do not necessarily require violence for their generation. Airy's attention was drawn to peculiar fluctuations of the tide at Malta which were quite appreciable in the years 1871 and 1872*. They occurred usually in a tranquil sea, as simple-harmonic variations of great regularity with a periodicity of about 21 minutes and a vertical range of some 12 inches. Having just heard of Forel's investigations on the Lake of Geneva, Airy at once concluded that the phenomenon was similar to the lake-seiches, and he conceived the seiches at Malta to be the result of wave reflections between the shores of Sicily and Africa. It is to Airy's credit that he was possibly the first to realise that seiches could occur on coastlines as well as in lakes, even before Forel himself had accepted this possibility, but he was probably wrong in associating a seiche of 21 minutes periodicity with reflecion effects produced between the coasts of Sicily and Africa. In reality the seiche must have been peculiar to the single small bight in the coastline of Malta where the tides were measured. Nevertheless, Airy makes a further interesting comment that seiches with intervals of 15 or 20 minutes had also been registered at Swansea, in Wales.

Darwin† also had noticed in the trace of the tide-gauge at Bombay irregularities with periods ranging from a few minutes to

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* 'On the Tides at Malta'; Phil.Trans.Roy.Soc.,London,Vol.169,1878,[47],p.136.

† L.c. (ante p. 38), [28], p.43.

over quarter of an hour, and while not subscribing immediately to the view that they were seiches, he recognized their affinity, and, in common with Forel, was content to call them vibrations of the sea. Numberous other investigators took up the study of what were then currently called the 'Secondary Undulations' of the tides, Duff and Denison in Canada, Russell in Australia, and Platania in Italy being prominently connected with the subject at the turn of the century. These investigators all came to the conclusion that the effects observed were connected with barometric disturbances over the ocean.

Between 1903 and 1908 the phenomenon was very intensively studied by Professor Omori and his associates Honda, Terada and Isitani in Japan as a part-undertaking of the Japanese Earthquake Investigation Committee*. After measurements of some 60 bays of the Japanese islands they showed conclusively that the secondary oscillations depended for their periodicity upon the configuration of the coastline, and that the periodicity could even be calculated with fair approximation from the basic dimensions of the bay, on the supposition that the oscillation partook of the nature of a uninodal seiche with the node at the mouth of the bay. They attributed the secondary undulations to long waves generated by fluctuations of barometric pressure, wind or earthquakes in the open ocean, confirming thereby the deductions of previous investigators.

Professor Chrystal in his concluding report (1908) on the seiches in the Scottish lakes, refers to the corresponding sea-phenomenon by remarking†:

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*Honda, Terada & Isitani: 'Secondary Undulations of Oceanic Tides'; Phil. Mag., Vol. 15, 1908, [48], p. 88 et seq.

†L.c. (ante p. 86), [42].

> "These oscillations (in bays) which are sometimes of considerable range, are apparently due to resonance with comparatively inconspicuous undulations in the external oceanic swell, the periods of which are equal to some of the natural periods of the bay."

and Darwin, in the later edition of his book (1910), comments*:

> "It now seems to be well established that landlocked arms of the sea and bays have their regular seiche-like oscillations.....The vibrations are almost certainly produced by differences of barometric pressure, but the periods of oscillation must be determined almost entirely by the configuration of the inlet....."

From this stage onward the mathematicians picked up the threads and by applying Chrystal's work to bays were able to explain most of the peculiar oscillations occurring: Harris in America (1908), Proudman (1914), Doodson (1920), Goldsbrough (1930), and Lamb (1932) in Britain, and Defant in Europe (1929) were prominent in this field.

Marmer (1926)† gives, finally, as up-to-date an explanation of the phenomenon as could be found when the author embarked upon the Investigation of Range:

> "The exciting cause of the seiche may be sudden changes in barometric pressure, strong winds, or waves from the sea. In the open sea waves of various periods appear to exist and as these proceed towards the coast the one whose period approximates to the period of the body of water opening into the sea will bring about a seiche in that body of water.
>
> "Seiches occur most frequently in deep bays or estuaries that are nearly landlocked. But they may also be found in any portion of the sea partly bounded by land, for any such area is capable of sustaining stationary wave oscillations of a period conditioned by its length and depth."

Marmer gives an interesting example of seiches generated in San Francisco Bay by a barometric depression on November 21, 1910, and this we reproduce in Fig. 26 as demonstrable proof of this mode of excitation. The predominant oscillations in this marigram have a period of about 48 minutes, but there is also evidence of a secondary 17 minute periodicity. From observations and model experiments, San Francisco Bay has now been shown to have several distinct modes of oscillation yielding periodicities of 17-19, 24-27, 34-41, 47 and 116 minutes§, which become prominent according to the circumstances of the disturbing agency.

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* L.c. (ante p. 38), [28], p. 57.

† 'The Tide' (New York), 1926, [49], pp. 146-165.

§ Cf. Laugharne Thornton: 'Seismic Sea Waves'; Engineering, My 1946, [50], p. 484.

CHAPTER VI.

OCEAN-WAVES.

" As by the west wind driv'n, the ocean waves
Dash forward on the far resounding shore
Wave upon wave;...."

—— Homer,
The Iliad, IV, (800 B.C.).

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35. Sea-Vibrations.

The findings of the last chapter establish that irregular coastlines fronting on the ocean are subject to the same general phenomenon as inland lakes, and have their own seiches. But in the same way that Forel, Chrystal and Darwin saw fit to differentiate between the true lake-seiches and what they called 'vibrations', so we may divine a distinction between the coastal seiches and the vibrations of the sea. These latter also give rise to a dense embroidery on the marigrams traced by harbour tide-gauges and have periodicities in general greater than the visible storm waves. It is logical to apply to these sea-vibrations the same conclusions as were drawn in respect of lake-vibrations (Section 32), and it would appear therefore that their existence is to be attributed to ocean-waves of exceptional length, generated by wind or pressure-disturbances. We are at once led to enquire further into the nature of ocean-waves with the object of defining the connection between sea-vibrations and the Range-phenomenon.

36. Types of Waves.

In his great classic study of waves Scott Russell*

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* 'Report on Waves'; Report of the Brit. Assoc. for the Advancement of Science, 1844, [51], pp. 311-390.

recognised four types, which he classified in orders. Only waves of the first two orders concern us here: these are waves of translation and waves of oscillation, the distinction lying in the fact that there is mass-transport of water in the first type, which is solitary, while there is only elliptical motion of water particles in the second, which is inclined to occur in groups. The solitary wave has a crest and no trough and derives from the sudden addition or displacement of a mass of water in an otherwise tranquil body of water. Waves of oscillation, (representing wind waves, ocean swell and even tidal waves) tend to assume the properties of waves of translation in shoaling water where they are caused to break or accumulate in the form of tidal bores[*]. The solitary wave of translation may be regarded as an extreme case of oscillatory waves in which the wave-length is very great compared with the depth, with the result that the crests are virtually independent of each other[†]. Boussinesq and Raleigh both independently succeeded in applying hydrodynamical theory to this type of wave and derived the formula for its velocity which agreed precisely with the empirical formula devised by Scott Russell to fit his experimental results. Here was a particularly beautiful example of concordance between theory and experiment, and it is the more remarkable in that Airy had previously claimed that his results, by approximate theory, fitted the observations, a contention which was vehemently refuted by Scott Russell in the interests of scientific accuracy.

As will be apparent from the quotation given in Chapter I

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[*] Scott Russell himself made this observation: Cf. also Bigelow & Edmondson, 'Wind Waves at Sea, Breakers and Surf',(Washington),1947,[52], p.115; Brown, 'The Flow of Water in Tidal Canals', Trans. Am. Soc. C.E., Vol.96, 1932, [53], pp.749-834.

[†] Cf. Lamb, 'Hydrodynamics',(Cambridge),1932,[54],Art.252,p.423.

(p. 11), the rollers and ocean-swell off the Cape of Good Hope, with which we shall have to deal, were classed as waves of translation by Scott Russell himself. In what follows we shall nevertheless pay some attention to waves of oscillation, bearing in mind the observation already made that waves of translation are a particular limiting type of oscillatory waves.

Waves of oscillation, having a finite amplitude which is commensurable with the wave length, have a surface profile which is very nearly trochoidal[*]. This was first demonstrated theoretically by Stokes and has since been verified experimentally by observation and measurement of natural and artificial waves[†]. In this form the wave crests are sharper and the troughs flatter than in a pure sinusoidal profile, and it is probable that very high waves in deep water approximate to this shape. When the amplitude is small compared with the wave-length the profile becomes sinusoidal and this is the form most characteristic of long waves and ocean-swell. Comprehensive experiments with electrical recording equipment off the coast of Algiers[§] have verified that the profile of heavy swells is in fact very closely sinusoidal.

Oscillatory waves have been shown, both in theory and practice, to give rise to a small momentum of the wave particles which is progressive in the direction of wave travel[‡].

37. Properties of Oscillatory Waves.

On the basis that the amplitude, A, of an oscillatory

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[*] Cf. Lamb, (l.c. ante p. 105), [54], Art. 250, p. 417.

[†] 'A Summary of the Theory of Oscillatory Waves', Technical Report No. 2, Beach Erosion Board, (Washington), 1942, [55], p. 24.

[§] Renaud: 'The Port of Algiers: Observations on Swell'; Account of the 16th International Navigation Congress, Brussels, 1935, [56], pp. 385-392.

[‡] Cf. Lamb, (ibid.), [54], Art. 250, p. 419.

wave is small compared with the wave-length, λ , and the depth, d , of water, the canonical equation for the velocity of the wave is

$$c = \sqrt{\frac{g\lambda}{2\pi} \tanh \frac{2\pi d}{\lambda}} \tag{1}$$[*]

where g is the acceleration due to gravity. This presupposes that the waves are large enough to render surface tension of small account, and that the motion is irrotational, without vorticity. Although turbulence is set up by flow of water across rough boundary surfaces, the low viscosity of water prevents rapid permeation and this factor is not ordinarily important in wave motion.

By writing

$$p = \frac{2\pi}{\tau} \tag{2}$$

and

$$q = \frac{2\pi}{\lambda} \tag{3}$$

where τ is the period of the wave, equation (1) can be transformed to:

$$c = \sqrt{gd\left(\frac{\tanh qd}{qd}\right)} \tag{4}$$

Further, by noting that

$$\lambda = c.\tau \tag{5}$$

equation (1) may also be expressed in the form:

$$c = \frac{g}{p}.\tanh\left(\frac{pd}{c}\right) \tag{6}$$

It is interesting to record, in passing, that equation (1) was presaged by Newton in 1686, when he concluded that:

> "The velocity of waves varies as the square root of the breadths"[†].

From (1) and (4) it will be obvious that when the hyperbolic tangent approximates to unity, the velocity is given by

$$c = \sqrt{\frac{g}{q}} = \sqrt{\frac{g\lambda}{2\pi}} \tag{7}$$

This appbies to all waves whose wave-length is less than twice the depth of water. On the other hand, all waves whose wave-length is large compared with the depth, are propagated with a

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[*] Cf. Lamb, (l.c. ante p. 105), [54], Art. 229, p. 367.

[†] That is, wave-lengths; 'Principia', 1686, [57], Book II, Theorem 36.

speed approximating to $c = \sqrt{gd}$ ——————(8)
since the hyperbolic tangent tends to the value qd when d/λ is small.

If the progression of the wave in a constant depth of water be referred to a coordinate system XOZ whose origin O lies in the plane of the undisturbed surface of the water and whose OX axis is horizontal and positive in the direction of wave travel, the OZ axis being vertical and positive upwards, the equations for the component displacements (ξ, η) of any particular water particle (x, z) may be written*

$$\left.\begin{aligned} &\text{(i)} \quad \xi = A.\frac{\cosh q(z+d)}{\sinh qd}.\cos(qx-pt) \quad \text{(horizontally)} \\ &\text{(ii)} \quad \eta = A.\frac{\sinh q(z+d)}{\sinh qd}\sin(qx-pt) \quad \text{(vertically),} \end{aligned}\right\} (9)$$

where t is the elapsed time. Equations (4) are the parameters of the elliptic-harmonic orbit of the water particle, its periodicity being the same as that of the wave.

From equation (9)-(i) we see that the hyberbolic factor varies from $1/\tanh qd$ at the surface $(z=0)$ to $1/\sinh qd$ at the bottom $(z=-d)$. For long waves where λ is large compared with d, the hyperbolic sine and tangent are of the same order, and the horizontal movement of water is thus sensibly the same at all depths. The vertical movement, of course, varies from $2A$ at the surface to zero at the bottom. The ratio of bottom to surface horizontal movement, in the general case, is $1/\cosh qd$.

The wave-lengths, speeds and movements of oscillatory waves of various periodicities may be examined with benefit on a diagram of the form of Fig. 27. Consider, for example, a wave of 15 seconds periodicity advancing from deep water, ($d=$ 10,000 feet, say), towards a shelving coast. Fig. 27

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* Cf. Lamb, (l.c. ante p. 105), [54], Art. 229. p. 367.

shows that its wave-length and speed remain constant at about 1140 feet and 80 feet/sec. respectively until the water depth has reduced to 1000 feet. In all this time the water particles at the sea bottom have hardly been disturbed, but as the water shoals further, the wave-length of the wave becomes contracted and its advance progressively slower, while the oscillatory movement is communicated more and more to the water particles on the sea-bed. By the time the wave has entered 15 feet of water the horizontal movement on the bottom is theoretically 95% of the surface movement; wave-length is 320 feet, and velocity only 22 ft./sec., or 15 mph.

The shaded bands on the diagram indicate the progressive increase in oscillatory movement at the sea-bottom, ratios relative to surface movement being given by the diagonal dash-dot lines. In the deeply shaded portion of the diagram the movement is virtually solid from surface to bottom. Here it will be noticed the periodicity lines are all almost parallel and conform to equation (8) for long waves. The unshaded portion of the diagram conforms to equation (7) for short waves in deep water. In the transition zone between the dash-dot diagonal lines, neither of equations (7) or (8) is accurate and the properties of the wave must be evaluated from the full equation (1), (4) or (6). In plotting Fig. 27 the author used for the most part equation (6), in which the value of C involved in the hyperbolic tangent was estimated beforehand from a judicious use of equations (7) and (8). By that means C could be more accurately calculated from (6) and a second approximation made if necessary, until its correct value was found.

In comparison with these small-amplitude waves, trochoidal waves of finite amplitude progress with a velocity approximating to

$$c = \sqrt{\frac{g}{q}(1+q^2A^2)} \qquad (10)$$ [*]

This, in point of fact, is very little different from equation (7), even for waves of appreciable amplitude. Consider, for instance, 10 second waves, for which, in deep water, the wave-length is about 500 feet, (Fig. 27). If these waves have a height, $2A$, of 50 feet, which by ordinary standards is very considerable, the influence of the term $(qA)^2$ will still only be such as to increase the value of the velocity, as given by equation (7), by $(\sqrt{1+0{\cdot}1}-1)$ or about 5%. For 15 and 20 second waves, which are the only other types which ever attain to great heights, 'tidal' waves excepted, the differences are smaller still. The effect of limited depth upon these trochoidal waves does not appear to have been investigated by Stokes and his successors, and we must presume that in shallow water too the chart of Fig. 27 is not greatly in error even for waves of fair amplitude.

Scott Russell's solitary wave of translation has a velocity of

$$c = \sqrt{g(d+A)} \qquad (11)$$

which, but for the inclusion of the amplitude, is the same as equation (8). This formula really only begins to apply after a wave has broken or been retarded to the point of an accumulation in a shallow estuary[†]. Most long waves such as are depicted within the shaded zone of Fig. 27, are waves of translation in the sense that they constitute a solid mass-movement of water over the sea-bed, but, unlike the solitary wave, the motion is reversible, as indeed it must be to produce a seiche-phenomenon.

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[*] Cf. Lamb, (l.c. ante p. 105), [54]. Art. 250. p. 417.

[†] Cf. Allen: 'Experiments on Water Waves of Translation in Small Channels', Phil. Mag., May, 1938, [58]. pp. 754-768.

Long waves in general tend to have much smaller amplitudes than the visible wind-waves and swell, and the assumption that amplitudes be small in comparison with wave-length and depth is really more satisfactorily observed with them than with short waves of the latter type. Our general conclusion therefore is that Fig. 27 will apply with sufficient accuracy to all the types of waves with which we are likely to be concerned, regardless of their magnitudes in height.

38. Group-Velocity of Waves.

The wave-velocities of Fig. 27 apply to individual waves, but when groups of waves of slightly different periodicities are propagated in the same direction they interfere to produce the phenomenon of 'beats' in which the resultant waves travel in separated groups whose velocity as a whole is less than the velocity of the individual waves comprising them. This phenomenon appears to have been observed first by Scott Russell[*], who recorded:

> "....the velocity of wave transmission may be very different from the velocity of wave propagation."

He describes how a particular wave is seen to advance through a group, only to disappear in the front while its place is taken by another wave that has grown in size from the rear.

Stokes showed that this group velocity, U , in terms of the wave-length of the waves comprising the group and the depth of water, may be represented by the formula:

$$U = \frac{1}{2}c\left(1 + \frac{2qd}{\sinh 2qd}\right)^{\dagger} \qquad \text{\_\_\_\_\_\_\_\_\_\_\_\_}(12)$$

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[*] L.c. (ante p. 104), [51], p. 369.

[†] Cf. Lamb, (l.c. ante p. 105), [54], Art. 236, p. 381.

When the depth is great compared with the wave-length, as with short waves falling in the unshaded zone of Fig. 27, the group-velocity, U, is half the wave velocity, but when the depth is relatively small, U has the same value as c. For all long waves falling within the deeply shaded band to the left of the 0.95 diagonal line (Fig. 27), the group-velocity will be the same as the wave-velocity, since d/λ in this zone will everywhere be less than 1/20 (the value along the diagonal), making $U = 0.97c$ or better.

It is clear from this that in a mixed assortment of waves originating from a disturbance in deep water, the long waves will outstrip the short ones owing to their far greater group velocities. Short waves, while proceeding slowly at first as groups in relation to their individual waves, will gather speed relatively as they progress towards shallower water, until in the final stages, as Fig. 27 shows, when they enter the deeply shaded band, their velocities will be equal. Since even 5 second waves cut the shaded band of Fig. 27, it follows that we should look in vain for the phenomenon of waves, rising from the rear of a group, advancing through it and dying at the front, in ordinary sea-waves close inshore.

39. Wind-Waves and Swell.

Helmholtz showed that waves tend to be generated at the surface of discontinuity between two fluid media of different densities, travelling at different velocities across each other*. Such conditions prevail on the surface of the sea where the wind generates waves by traction across the interface between air and water.

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*Cf. Brunt, 'Physics of the Atmosphere', Glazebrook's Dictionary of Applied Physics, (London), 1923, [59], Vol. III, p. 38.

Jeffreys[*], in investigating the relationship between wind and wave-velocities, concluded that the wind can only supply energy to the waves so long as their velocity is less than that of the wind. Since wind-velocities, even in hurricane-force, do not run much above 100 mph, it follows from Fig. 27 that, in deep water, periodicities of ordinary wind-generated waves cannot much exceed about 20 seconds. This is confirmed by the many observations that have now been made on ocean-waves and swell. Vaughan Cornish[†], who spent a lifetime making scientific observations of waves in all parts of the world, never discovered visible waves above 22½ seconds in period: comparatively rarely too did he see waves of the order of 19 and 20 seconds. The longest period on record for a visible swell appears to be 26 seconds, experienced off the coast of England. For the most part visible waves and swell have been found to lie within the periodicity range of from 5 to 15 seconds with the emphasis between 7 and 9 seconds[§].

The heights to which wind-waves attain have been found to bear an approximate lineal relationship to the wind-speed, but length of fetch is also a factor influencing the height. Thomas Stevenson[‡] in 1850 made observations in the Firth of Forth and the Moray Firth, as well as on a fresh-water loch, in Scotland, and concluded that wave-height was proportional to the square root of the length of fetch. His formula, $2A = 1{\cdot}5\sqrt{f}$ for height in feet and fetch, f, in miles, is still currently accepted as an

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[*] Additional Notes to Vaughan Cornish's 'Ocean Waves',(Cambridge),1934,[60].

[†] 'Ocean Waves and Kindred Geophysical Phenomena',(Cambridge),1934,[60]; also 'Waves of the Sea and Other Water Waves'(London),1910,[61].

[§] Cf. Seiwell,'Results of Research on Surface Waves of the Western North Atlantic', Paper in Physical Oceanography and Meteorology, Mass. Inst. Tech.& Woods Hole Ocean.Inst., 1947,[62], Vol. 10, No. 4; also Bigelow and Edmondson (l.c.ante p.105),[52],pp.26-37; Sverdrup, Johnson and Fleming, 'The Oceans',(New York),1942,[63], Chap. XIV.

[‡] L.c. (ante p. 11), [5], pp. 19-29.

empirical rule for estimating wave-heights, and appears to agree with Cornish's observations.

The general consensus of opinion now is that the vast majority of all waves in all parts of the oceans are not above 12 feet in height and that the frequency of greater heights than this is only about 20%. As an indication of the relationships likely to prevail between wind-speed and wave-proportions, we reproduce below the table of Cornish, generalising his observations:

Table I: Properties of Wind-Waves at Sea.

Wind Speed mph. (1)	Wave Speed mph. C (2)=0.8 (1)	Period secs. τ $(3)=\frac{2}{7}(2)$	Wave-length feet λ $(4)=\frac{41}{8}(3)$	Height feet $2A$ (5)=0.7(1)	Length-height Ratio (6)
31	25	7	250	22	11.6
35	28	8	330	24½	13.3
42	33½	9½	470	29½	16.0
50	40	11½	670	35	19.0
59	47	13½	930	41½	22.6
68	54½	15½	1230	47½	25.9

In the intervening years since the author commenced his studies of the Range problem, great attention has been concentrated on the subject of ocean-waves and swells. During the last war the forecasting of swells was an important prelude to invasion-landings and the study naturally received the full support of military exigency. By means of sensitive recording apparatus and new analytical techniques*, swells arriving on the coasts of England have been traced back incredible distances to

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* Cf. Barber and Ursell, 'The Generation and Propagation of Ocean Waves and Swell', Phil. Trans. Roy.Soc.Lond., Vol. 240, 1948, [64], pp. 527-560; also Barber, 'Ocean Waves and Swell', Dock & Harb. Authy., March 1949, [65], p.280; Deacon, 'Waves and Swell', Quart. J. Roy.Met.Soc., July, 1949, [66], pp. 227-238.

their origins in storm-centres travelling across the North or South Atlantic. We propose to deal more fully with these findings in a later part of this work, but for the present it is sufficient to say that they substantiate very largely the information and deductions presented above.

Once waves have escaped from a storm-centre where they have been under the domination of winds, they are propagated as smooth swells under the influence of gravity and friction only. The fact that swells are able to escape at all from their faster generating winds must, of course, be ascribed to the gradual dispersion of the winds outwards across concentric isobars of the depressions, which are usually the focal points of genesis for waves, as also to the slower speeds (20-35 mph) of progression of these storms in comparison with those of the winds within them and of the waves.

The warning which swells are able to give of the approach of storms is proverbial and in the British Isles they have been known for generations as 'death-waves'. But in the South Atlantic where the islands of Ascension, St. Helena and Tristran da Cunha rise sheer from great depths of ocean, the swells reach their most impressive proportions. Webster's account of them in 1829 is classical*:

> " One of the most interesting phenomena at Ascension are the rollers; in other words, a heavy swell producing a high surf on the leeward shores of the island, occurring without any apparent cause. All is tranquil in the distance, the sea-breeze scarcely ripples the surface of the water, when a high swelling wave is suddenly observed rolling towards the island. At first it appears to move slowly forward, till at length it breaks on the outer reefs. The swell then increases, wave urges on wave, until it reaches the beach, where it bursts with tremendous fury."

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*Africa Pilot, (l.c. ante p. 36), [26], p.

An interesting example of the extent to which swell can be the precursor of a storm concerns the Bermudas hurricane of 1839[*]. The swell was observed on the southern shores of the islands three days before the arrival of the hurricane, and increased in intensity steadily with the approach of the cyclone.

40. Ground-Swells.

Scott Russell referred to the Cape rollers as ground-swells and waves of translation (p.11), and the implied meaning of this reference is clearly therefore to a wave that produces an oscillatory mass-movement of the water from surface to sea-bottom. Lacey[†] defines a ground-swell as the product of wind-waves generated in a distant part of the ocean: their effects, he says, penetrate to greater depths than ordinary waves, and on approaching shallow water they exert more powerful percussion-effect on sea walls, while their backwash is more destructive to beaches. Elsewhere Lacey remarks[§] that they are usually observed to set in after the lapse of strong winds. A somewhat similar observation is made by Mitchell[‡]:

> "....the long, smooth undulations of a heavy ground-swell, with their enormous destructive energy, occurring as they did after a storm had abated and when the weather was perhaps calm and fine, were the result of oscillations which had been gradually set up in a large mass of the sea by the wind."

While mariners and harbour engineers have always been conscious of ground-swells, the conception of their nature remains rather nebulous. Scott Russell, for instance, considered the Cape rollers of 15 to 20 second periodicity to be ground-

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[*] Stevenson, (l.c. ante p. 11), [5], p. 21.

[†] 'Sea Waves', Dock & Harbr. Auty., Jan., 1942, [67], pp. 45-48.

[§] 'Ocean Swells and Abnormal Tides', Engineering, Oct., 1937, [68], pp. 406-6.

[‡] Reply to discussion (l.c. ante p. 3), [1], p. 244.

swells, as well he might, since Fig. 27 shows that by the time they have entered 80 feet of water the bottom surge is 80% of the surface movement. But how are we to align this fact with the observations of Mitchell and Lacey that ground-swells develop after the lapse of winds and the abatement of a storm? Since ground-swells are necessarily long waves, should they not rather precede the wind than follow in its wake? If they are, in point of fact, wind-generated, as Lacey suggests, they must, in virtue of their greater velocities, outrun both the wind and the ordinary swell and thus anticipate the latters' arrival. The recent work of Barber and Ursell* shows that the 15 to 25 second swells definitely precede the shorter ones, their order of arrival being strictly in accordance with the theoretical dictates of their relative speeds. This anomaly must then await elucidation from our own investigations in the course of succeeding pages.

At this stage we may venture to offer an interpretation of a ground-swell as being any particular wave which within a depth of say 80 feet of water (in the precincts of a coast, bay or harbour), exhibits an oscillatory mass-movement of water of which the surge on the sea bottom is at least 80% of that at the surface. According to this definition all waves falling within the shaded zone to the left of the 0.80 diagonal line of Fig. 27 will be ground-swells.

As the discussions of Section 39 have revealed, 25 seconds appears to be the approximate upper limit of visible swells. The gradual diminution in magnitude of the swells as they approach this limit is well portrayed in Barber and Ursell's wave spectra. Unfortunately the frequency band of sensitivity of

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* L.c. (ante p. 114), [64].

their recording instrument does not seem to have been wide enough to register swell-periodicities above 30 seconds and there is no evidence from this source of still longer swells preceding the visible ones. The use of a pressure recorder on the sea bottom, in open water, is in any case not the most satisfactory way of trying to measure extremely long ground-swells, since it is almost certain that their negligible amplitude will produce no vertical pressure worth recording.

It seems that the existence of the invisible long waves of the sea, similar to those detected by Forel and Chrystal in lakes, must be inferred from the embroidery on the marigrams of tide-gauges located at points where, through shelving ground and reflection, they can accumulate to measurable proportions. Recently, however, (1948), an instrument has been brought into use at the end of the Scripps Océanographic Institution's Pier at La Jolla, California[*], which, through special design, is able to detect wave periodicities up to 25 hours; but gives best response to wave-periods between 1½ minutes and 2½ hours. Records so far obtained apparently prove the existence of complex wave-systems within these frequency-bands, but further details have not yet come to the notice of the author.[†]

41. The Destructive Power of Ground-Swells.

The accounts are legion of the havoc and destruction wrought by long waves in harbours and along coasts. The most dangerous ground-swells, visible and invisible, originate from the centres of the equatorial cyclonic storms, as has been proved

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[*] Munk, Inglesias & Folsom,'An Instrument for Recording Ultra Low Frequency Ocean Waves', Review of Sc.Instru.,Vol.19, Oct.,1948,[69], pp.654-658.

[†] Some particulars have now been published in a paper by W.H.Munk; 'Surf Beats', Trans.Am.Geophys.Union.,Vol.30,Dec.,1949,[125],pp.849-854.

repeatedly by the subsequent devastating inundations marking the arrival of the cyclones themselves. If the track of an intense cyclone crosses a coast, as it sometimes does, the chances are that great waves of the character of seismic sea-waves will flood the shore. But even if the cyclone veers off from the land it will often send great waves rolling towards the coast, capable of wreaking enormous damage.

The Coromandel (east) coast of India is much subject in this way to the invasion of cyclones originating in the Gulf of Bengal[*]. During the south-west monsoons of the May period the cyclone-tracks swing northward clear of the land, but in the north-east monsoon period of October, the cyclone-tracks are westward towards the coast and only swing northwards at a late stage. It has always been a mystery why the shore-line along the Coromandel coast accretes with the south-west monsoons and erodes with the north-east, but it is probable that the explanation lies in the essentially different character of the waves in the two seasons. Mild and distant cyclones would give rise to weak ground-swells and short-period oscillatory waves whose forward momentum (p. 106) could be expected to occasion a sand-drift shorewards, while intense and proximate cyclones would generate strong ground-swells, whose powerful backwash could easily provide the denuding agency.

The destructive nature of big waves experienced along the Californian coast of North America has been vividly described by McEwen[†] and by Leypold[§]. The latter has presented convincing arguments for associating severe beach-erosion

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[*] Cf. Lacey, 'The Coromandel Coast of South India', Dock & Harbr. Authy., Dec., 1943, and Feb., 1944, [70], p. 181 et seq.

[†] 'Destructive High Waves along the Southern California Coast', Shore & Beach, April, 1935, [71].

[§] 'California Seiches and Phillipine Typhoons', Proc. United States Naval Inst., Vol. 63, 1937, [72], pp. 775-788.

there with coastal seiches of the shorter-period types, developing from the long waves spread by Pacific typhoons and cyclones, 5000 miles away. That this is not as fantastic as it may seem, is now revealed by the fact that weak ground-swells, originating off Cape Horn, have been detected on the coasts of Britain, 6000 miles from their source*.

Wherever cyclonic storms and travelling depressions are cradled into being over the wide expanses of oceans the story is the same. Off the east coast of Madagascar the cyclone-tracks run on a W.S.W. course but swing southward usually before they reach the coast: hurricanes play over the east and west coasts of Australia with the same directional sweep, and south-eastwards across Cape Horn in South America. In the northern hemisphere the trend of hurricanes and typhoons is north-westwards against the east coasts of America, Asia and India. In higher latitudes the spawning grounds of the more common travelling depressions are located near the barometric high-pressure belts over the oceans, and the directions of travel are from west to east. As Lacey has shown†, these cyclonic depressions, although much less violent than the cyclones, hurricanes and typhoons of the equatorial regions, are capable of raising phenomenal waves and tides, and are a prolific source of ground-swells.

42. The Connection between Ocean-Waves and Range-Action.

We now return to our basic enquiry as to which of the many possible ocean-waves are responsible for Range-action. The answer has been partly anticipated by the contents of

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* L.c. (ante p. 114), [64], p. 550.

† 'Abnormal Tides in the Thames', Engineering, Aug., 1936, [73], p.178; also l.c. (ante p. 116), [68].

Chapter IV, but there remains to examine the records in literature of Range phenomena in other ports.

The earliest reference that the author has been able to trace comes from Thomas Stevenson* in 1868, who, in discussing the natural causes which tend to prevent the silting up of harbour entrances, remarks:

> " The ordinary waves produced by a gale and the 'run', wherever there is a ground-swell, are, I think, the agents which possess all the powers that are required."

Although Stevenson apparently made no other special mention of 'run', there was obviously no doubt in his mind of its dependence on ground-swells, as distinct from ordinary waves.

Cunningham in his work of 1910† makes no mention of Run but refers to 'scend' (often a synonymous term for it) in his later book of 1918§. Here he points out the necessity for providing extra depth of water in harbours where Scend is troublesome, to prevent ships from fouling the bottom. He quotes the case of the S.S. 'Cufic', which with a draught of 28 feet fouled sea bottom in a depth of 39 feet of water, while entering Port Philip, near Melbourne, in heavy swell.

The first really comprehensive references to Range action are to be found in a series of papers on wave-action in harbours prepared as a symposium for discussion before the Institution of Civil Engineers, London, in 1919‡. In the second of these, Hindmarsh defines 'Range' as sea-action: in the third paper, Sandeman gives Range a more specific meaning. He proposes that the term should apply only to waves from the sea that have penetrated into a harbour, as distinct from short wind-waves

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* L.c. (ante p. 11), [5].
† 'Dock Engineering', (London), 1910, [74].
§ 'Harbour Engineering', (London), 1918, [75].
‡ L.c. (ante p. 3), [1], pp. 178-250.

that have been whipped up inside the basins. Sandeman records that Range-waves from 6 to 24 inches in height with periods of from 40 seconds to 2½ minutes were experienced in the harbour of Blyth, facing the North Sea: the momentum imparted to heavy ships with slack moorings had frequently proved sufficient to break steel hawsers up to 5 ins. in circumference. The first and the fourth papers describe the North Sea harbours of Whitby and Sunderland respectively where the problems of Range had to a large extent been overcome by the construction of enveloping, outer breakwaters: their authors, Mitchell and Simpson, do not, however, attempt to define Range other than as an ingress of swell into the dock areas.

In the resulting discussion Sir Francis Sprigg gave as his interpretation of Range:

> " ....the surging and shifting, to and fro and round about, of the deep solid body of water in a harbour, due to the repeated access of swell from the outside through the entrance, a movement acting so deeply as to carry with it heavy vessels for a distance perhaps of three or four feet bow-wards or stern-wards two or more times in a minute, with a force which might easily snap a 6-inch wire line or a 15-inch coir spring."

Sprigg considered that the translatory nature of the swell in the shallower depths of a harbour would tend to raise the level of the enclosed water, which would be balanced by an outrunning current, perhaps in the lower half of the depth at the entrance. The result of this simultaneous inflow and outpour would be a surging movement of the mass of the enclosed water. He cited as an example of this the movement that occurred in Madras harbour:

> 'Even in the enclosed 9-acre 'boat basin' at Madras with its 80 ft. entrance and 12 ft. depth, 3/4 mile in from the 400 ft. main harbour entrance, the effect of Range had been most troublesome for a few hours at a time, all the small craft from his own dredgers downwards, that had taken shelter in the basin, being slowly moved about a foot or two forwards and backwards with a force that could with difficulty be withstood by the necessarily short lines and cables with which they had been moored; and all this with no waves to speak of."

Sprigg remarked further that Range of this character occurred at Madras only during a couple of months of the year, and then perhaps only on one or two days of those months.

Mitchell in his reply to the discussion introduced the idea of ground-swells being responsible for Range-action, as we have already recorded (p. 116). His further account of the phenomenon goes far towards explaining it. The whole body of water in a harbour, he contended, was gradually set in oscillation by the impression on the entrance, in regular pulses, of enormous quantities of energy derived from the incoming waves. In many harbours there would probably be more than one period of oscillation, the periods depending on the volumes of the water-masses, their shape in plan and section. Amplitudes would depend on the energy-input and friction-losses and the degree to which the period of swing agreed with that of the entering waves. Although Mitchell refers to the work done on analogous oscillations in well-known lakes, and was thus the only harbour engineer among the many prominent men taking part in the discussions to be aware of the phenomenon of seiches, he does not actually introduce this term.

The positive connection between coastal seiches and Range-action was established experimentally in 1935 by Barillon* in respect of the harbour of Tamatave on the east coast of Madagascar. Here ships were found to break their moorings by responding to strong surges with a periodicity of the order of a minute, when the visible swell out in the roadstead had a period of only about 10 seconds. On constructing a model of the bay and harbour Barillon found that by impressing upon it paddle-generated swells of certain periods, resonant oscillations could be induced alongside the quays. These resonant

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* 'Mouvement de Seiche dans une Baie', Rev. Gen. de l'Hydraulique, Jan., 1938, [76], pp. 3-6.

frequencies seemed to be related to each other and were not altogether dissimilar from the calculated critical modes of oscillation for the bay of Tamatave, regarded as a semi-conical canal open to the sea at its wide extremity. Sofar as is known this was the first practical demonstration by model of this type of problem. Barillon had been led to this line of investigation by Defant's account of sea-vibrations and of the work of Chrystal and Forel. Barillon's studies were incomplete, however, and required substantiation from actual prototype measurements.

If Barillon's was the first model-study to be made of the Range-phenomenon, it is certain that at that time the problem was already well understood by Leypoldt* and others in America. Most of the large harbours along the Californian coast exhibited the marigram-embroidery, characteristic of Range, and a certain amount of trouble had been experienced in the mooring of ships. The first experimental study of Range to be undertaken in the United States (Los Angeles Harbour) appears to have been initiated at about the same time as the author commenced his researches at Cape Town. Model investigations were undertaken at the California Institute of Technology, Pasadena, under the direction of Professor Knapp, and also more comprehensively at the Vicksburg Engineering Experiment Station. Since that time a great many more model-studies of wave and surge problems have been instituted at Vicksburg in connection with Anaheim Bay and Monterey Harbour, California, and the Midway Islands, Hawaii†.

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* L.c. (ante p. 119), [72]; also 'San Francisco Bay Tides', Proc. U.S. Naval Institute, Vol. 65, 1939, [77], pp. 1270-1276.

† Hydraulic Research in the United States, U.S.Dept. of Commerce, (Washington), Vol. XI, 1947, [78], pp. 85, 86, 89.

The special difficulties encountered at Los Angeles as a result of Range are described by Leypold in a discussion on a paper by Edwards and Soucek, dealing with surges in the Panama Canal*:

> " In Los Angeles Harbor, numerous continuous seiches occur. Those with relatively long periods have little or no effect on ship maneuvering, whereas the short period seiches are a serious problem, especially in the naval base area where caisson gates for graving docks must be fitte into rather small keyways during the closing operation. The surges accompanying the seiches, with their rapid direction reversal, make the locking operation difficult."

Earlier Leypold accounted for these phenomena by saying that

> " Seiches in nature are produced chiefly by differences in barometric pressure on water surfaces in the same oscillating area, or by tidal effects."

Mr. George Stewart of the University of Cape Town anticipated the official investigation of the South African Railways and Harbours by constructing in 1941/42 a small, but useful, model of Table Bay Harbour for the purposes of studying the Range-problem. Although Stewart succeeded in reproducing the phenomenon in his model, his findings† do not reveal either a very deep study or a full understanding of the problem, and his conclusion that <u>swell</u> and <u>not sea</u> is the cause of Range requires qualifying.

The author had the opportunity of seeing Stewart's model in action in June, 1942, and cannot but concede that, whatever the failings of the model itself, it was nevertheless able to demonstrate the fundamental action that ensues. This action was very similar to that described by Sprigg and Mitchell (pp. 122-3) and was initiated by the formation of a multinodal seiche between the breakwater and the shore (Fig. 2). Differences of level between the water surfaces inside and outside the basins caused the flux, referred to by Mitchell

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* Proc. Am. Soc. C.E., May, 1944, [79], p. 764.

† 'Range-Action in Harbours', Journl.Inst.C.E.,Jan.,1943,[80],p.192.

as the pulsating stimulant, which, if the impressed periodicity was of the same order as the natural frequency for the basin, induced a sympathetic oscillation of the enclosed body of water.

From various verbal accounts that the author has received from time to time, it would seem that the Range phenomenon is common to many of the ports on the east coast of New Zealand and the west coast of Australia, and even to the Black Sea port of Batum.

There has also come to the author's notice - too late for adequate study unfortunately - the comprehensive series of papers presented at the 17th International Navigation Congress at Lisbon in 1949, dealing with the penetration of waves and swells into harbours. From these it is apparent that most of the ports of Chile, notably Santo Antonio, Iquique, Antofagasta, and Valparaiso, are afflicted with rather serious Range-troubles, which necessitate ships leaving the quays on occasion[*]. Significantly these are attributed to cyclonic storms over the Pacific. The conditions of resonance in harbours are studied by Messrs. Iribarren Cavanilles and Nogales Olano[†] with reference to several harbours on the coasts of Spain. The paper of Abecasis[§], dealing with Portugal's harbour of Leixoes (Porto), is of special interest, however, in that it reproduces marigrams for three points along the Portuguese seaboard, Leixoes, Lagos and Cascais, all of which show the typical embroidery of seiches caused by invisible ground-swells.

43. Digest of Current Knowledge about Range.

In this and the last chapter we have attempted to trace such information as is extant about the phenomenon of the sea

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[*] Report by Orego and Santander, Communication 4, 17th Internl.Nav. Congr., Lisbon, 1949, (Brussels), [81], pp. 23-30.

[†] 'Protection des Ports', (ibid.), [82], pp. 69-77.

[§] 'Le Port de Leixoes (Portugal)', (ibid.), [83], pp. 186-200.

known variously as Range, or Run, in the British Commonwealth, Surge in the United States, and 'Ressac', or Surf, in Europe.

There seems no longer any doubt but that Range, or Run, in harbours is the result of seiches or standing waves peculiar to the special shape and depth of harbour-basins, of bights and of bays and even of submarine canyons flanking the neighbouring coast-line itself.

The seiches are engendered by the reflections of incoming trains of waves or, alternatively, by the superposition locally of barometric fluctuations of quasi-periodic nature, and possibly by a combination of both, since intense winds and storms that blow home to a port are inevitably intrusions of atmospheric commotion.

There is now definite evidence that barometric disturbances over the oceans, in the form of cyclonic depressions in the high-pressure or polar-front regions, or their more violent counterparts such as cyclones, hurricanes and typhoons in the equatorial regions, give rise, not only to visible wind-waves and swells, but also to invisible ground-swells of great lengths, capable of travelling vast distances without change of form other than arises from shelving ground. Similar wave-trains may be caused by seismic upheavals, earthquakes, or tremors of terrestrial or submarine origin, but their incidence from this source is very much more sporadic.

These complex wave-trains contain waves of all periodicities and wave-lengths of which the longer ones precede the shorter. As with the ripples made by a stone falling into water, the long waves are of small height while the shorter waves carry more elevation. From this assortment, the submarine canyon, the bay, the bight, or the harbour-basin selects those waves whose periodicities most nearly agree with its own natural frequencies of oscillation, and under their stimulus gives asylum to the various multinodal seiches to which it is attuned.

Since a seiche constitutes a mass-movement of the whole body of water in an oscillating area, in which every particle of water moves synchronously with the same period and phase as every other particle, it is understandable how ships are adversely affected at quays where the boundary conditions are unfavourable and the movement is strong. The flux and reflux through basin-entrances, which is so characteristic of Range and gives rise to the term Run, is the necessary mode of impulsion whereby the external seiche or ground-swell communicates the oscillations to the inner basins.

Most of the harbours of the world are affected to some degree or other by the Range-phenomenon. Wherever the troubles are particularly severe it is noteworthy that the harbours front on wide expanses of ocean within the equatorial or polar-front belts, where travelling depressions or cyclones converge towards the harbours concerned.

CHAPTER VII

RECORD OF OBSERVATIONS AT CAPE TOWN.

> "....by noticing facts as they occur, without any attempt to influence the frequency of their occurrence or to vary the circumstances under which they occur; this is OBSERVATION:...."
>
> —Sir John Herschel,
> Discourse on the Study of
> Natural Philosophy,(1851).

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44. The Moral of Laboured Research.

The information given in the last two chapters was gleaned slowly over the years during which the research was in progress at Cape Town, and constitutes almost a complete, generalised explanation of the Range-phenomenon. The benefit of this understanding was, however, not wholly available to the author, for, although the main features of the phenomenon were recognized at an early stage, certain aspects which have become clearer in the light of publications since consulted, were still enigmatic at that time.

When the author took up residence at Cape Town in May, 1943, he was not yet aware, for instance, of Chrystal's work on seiches in the Scottish lochs, and for some time to come, owing to the heavy demands of model-designing and Range-measuring, he was unable to follow this important study. Chrystal's discovery of a direct connection between small barometric fluctuations and lake-seiches was in this way unknown to the author until after he had blundered independently on the same conclusion. Much the same sort of thing happened in respect of the use of graphical methods for charting wave-propagation which were devised to meet an exigency, as will be recounted, when unbeknown to the author at the time, similar methods had already been employed some years earlier. These are perhaps unfortunate examples of duplicated effort, but in the compelling circumstances in which the author had to work, with many irons in the fire and little help, they could not be avoided. In other ways too the author was obliged to grope his way forward under the impetus of his own observations and deductions, taking what guidance he could from the findings of literature, as and when time permitted of their study.

45. Measurement of Local Meteorological and Tide Conditions.

We have already mentioned that the tide-gauge and weather charts, which had provided such a profitable, if laborious, means of surveying the problem as a whole at the beginning, were compiled as regular routine throughout the Range-investigation. For that purpose the basic elements of weather were recorded on the spot by self-registering instruments. Winds in the dock area were recorded on a Dines Anemometer at the Look-out Station on the summit of the Grain-elevator, at an approximate altitude of 150 feet above sea-level. Barometric pressure was registered initially on an ordinary 8-day barograph, but, later, on a more sensitive instrument with wider pressure-scale. Temperatures were measured on an 8-day thermograph provided with 30 feet of mercury-in-steel, protected tubing connected to an exposure plate, which enabled the instrument to be kept in an office while its tentacle was exposed to shaded atmosphere outside. These last-mentioned instruments were located in the author's office at the Range Laboratory, Table Bay Harbour, at an approximate elevation of 50 feet above sea-level. Fig. 28 shows a corner of the office where the instruments were placed: two Lea self-recording tide-gauges are to be seen fixed to the wall on the right-hand-side of the photograph, of which however only one was ever in operation.

In Section 21 (p. 63) we remarked on the usefulness of the Lege tide-gauge in the Alfred Basin as an index of Range-action. In point of fact, however, the Lege gauge was able to register only such seiches as had a periodicity greater than about 4 minutes and was insensitive to the more troublesome vibrations of higher frequency, owing to its position at the dead-end of a chain of basins. The Lea tide-gauge in the Duncan Basin, on the other hand, was exposed to the commotion in a large basin linking directly with the sea. The marigrams from this gauge accordingly gave, on occasion, a denser embroidery, patterning the seiches in the Duncan Dock. As an index of Range of the troublesome kind, therefore, the Lea-recorder was still more useful, and had the added advantage of remote-control operation. In this respect it was a considerable boon, since installation of the autographic unit in the author's office, (which was far from the docks), enabled the incidence and development of Range-action to be watched and checked against meteorological conditions.

As might be expected of a uniformly rectangular basin, the Duncan Dock had two principal modes of oscillation, longitudinal and transverse, and the Lea tide-gauge was by chance favourably positioned to record both, (Fig. 4). The marigrams tended to show therefore mainly a combination of these two seiches, and their individual amplitudes were used in the plotting of Range-conditions on the later diagrams of the type of Figs. 14, 15 and 16.

Referring to Fig. 14b, it will be noted there are given, from the bottom of the diagram upwards, the wind-velocity, wind-direction, amplitude of oscillations (blue in the Duncan Basin, red in the Alfred Basin), tidal range barometric pressure, periodicity of oscillations, and finally temperature; all this in respect of Table Bay Harbour. Fig. 14 happens to contain also a comparison of corresponding data for Port Elizabeth Harbour.

The meaning of the diagram will become clear if we consider the conditions prevailing on any particular day, say June 21st, 1945, (Fig. 14b). At zero-hour the wind was blowing with an average velocity of 28 mph, with fluctuations between 8 and 46 mph limits, from due west. A longitudinal oscillation in the Duncan Basin of 1 inch amplitude and from 4.3 to 5.5 minutes period was in process of dying down (full line, blue zone): a transverse oscillation was co-existent, of amplitude 3 inches and period about 1.8 minutes (dash-line, blue zone). In the

Alfred Basin a 5½ minute seiche was still at its peak amplitude of 6.6 inches (dash-line, red zone), while a 10½ minute one had declined to an amplitude of 8½ inches (full line, red zone). At that time it was neap tide at the flood, level being 5 feet above L.W.O.S.T. Barometric pressure stood at 29.85 ins. and was dropping sharply, while air temperature was 57°F and had been fairly steady for the previous 24 hours, indicating overcast and probably rainy weather.

During the next 24 hours of that day, the wind after blowing more strongly for a bit, died away completely and veered to south-east. Transverse oscillation in the Duncan Dock became more subdued, while longitudinal oscillation increased in the afternoon. Surge in the Alfred Basin meanwhile declined steadily. Long-period seiches made themselves apparent from 6 hours onward (vide circles). The amplitudes of these were of the order of 3 ins. or less, and periodicities apparent were 20.6, 23.7, 18.4 and 60 minutes in the Duncan Basin (blue circles) and 60 minutes in the Alfred Basin (red circles). Mean sea-level rose slightly (about 7 ins.) above its average of 3 ft. above L.W.O.S.T. with the passage of the travelling depression which brought the barometric pressure down to its lowest value of 29.72 ins. at about 6 hours, after which pressure rose sharply again. The temperature dropped sharply to 53°F. roundabout noon with the crossing of the depression over Cape Town, and then rose quickly again to 60° at 16 hours, from which point it declined again.

By following these graphs in this way a complete picture of all the circumstances surrounding the development of Range at any stage can be seen in retrospect. At this stage we shall do no more than explain the interpretation of Figs. 14 and 15, and leave the detailed examination of them to a later part of this work, when further facts are at our command.

In passing, we may note that an approximate relationship is evident between the amplitudes of the 5½ minute surges in th Alfred Basin and the longitudinal and transverse seiches in the Duncan Basin: this is depicted in Fig. 29. We find here, however, a divergent scattering of plotted points with increase of amplitudes, implying a wide range of possible conditions. A surge of 10 ins. amplitude in the Alfred Basin, for instance, could, it seems, be accompanied by a transverse seiche in the Duncan Basin of anything from 2 to 7½ ins. amplitude, and a longitudinal one of from 1½ to 5 ins. amplitude.

46. The Embroidery of the Lea-gauge Marigrams.

Range-conditions in the Duncan Basin are, on the whole, well reflected by the embroidery on the marigrams of the Lea tide-gauge. Specific examples are given in Figs. 30 to 42 from which it will be seen that certain oscillations are clearly identifiable, notably the longitudinal and transverse seiches. Just how we divine that particular oscillations are an indication of such seiches will be disclosed in a later section of this chapter. The limitations of these marigrams lie in their constricted time-scale, which hides any oscillations of shorter period than about 1½ minutes. Evidence of possible multi-nodal seiches in the Duncan Basin must therefore be sought in the records of the seichometers, which we shall consider in due course, but, in the interim, information of very considerable interest and value may be gathered from a study of the Lea-gauge marigrams.

We present in Table II the apparent periodicities and amplitudes of conspicuous oscillations in the Duncan Basin, obtained from these marigrams for the years 1940 to 1945. Seiches of the order of 19 and 20 minutes and longer periods have not been included in the tabulation, which merely aims at bringing to light fundamental changes in certain periodicities.

Table II: Principal Oscillations in Duncan Basin, 1940-1945.

Year	Month	Day	Period τ and Range 2A of Seiche						Ships affected (Cf. Chap. I, Sectn. 6) and Remarks.
			Longitudinal				Transverse		
			τ mins.	2A ins.	τ mins.	2A ins.	τ mins.	2A ins.	
1940	May	26	7.00 6.90	5 7½	4.75 4.50	5 6	1.67	15	'Mauretania' C-berth. (p. 23)
	June	12	7.00 6.80	8 6	4.60 4.30	6 4½	1.81	18	
	June	14	7.10 7.00	6 9	4.50	4½	1.72	15	Entrance 750' wide.
	July	1-2	6.40	4½	4.67 4.90	4½ 4½	1.67 1.80	6 6	Entrance by this time reduced from 750' to 400'.
		23	6.66	4½	4.76*	4½	1.72*	6	
		25-6	-	-	4.85* 4.73	6 4½	1.73	6	
	Aug.	10	-	-	4.74	3	1.77	3	
		22-3	-	-	4.67	3	1.73 1.70	4½ 5	
	Sept.	7	7.32	5	4.58	9	1.64	9	
		23	6.83	5	4.50	4½	1.76	3	
		28	7.60	3	4.62	4½	1.67	4½	
	Oct.	16-7	6.64	3	4.17	5	1.77	6½	
		24-5	7.40	5	4.40	2	-	-	
1941	Aprl.	28	7.10	8	4.31	4½	1.68	5	
	June	2	6.67 6.50	6 6	4.75 4.25	4½ 8	1.78 1.70	9 11	'Clan McArthur' & 'Silverteak' (p. 24) Stub-berths.
		15	6.16	4	4.50	4	1.67	7	
	July	17	6.60	3	4.16	6	1.67	10½	
		28-9	-	-	4.55	3	1.50	7½	
	Aug.	2	-	-	5.00	3	1.87	12	
		9	6.75	3	-	-	-	-	
		10	6.60	3	4.30	3	1.86	6	
		15	6.90 6.00	4½ 4½	-	-	1.86	9	
		31-1	6.70	4½	4.20	9	1.86	12	'Lt. St. Loubert Bie', 'Brittanic', 'Kawsar', 'Glamma', 'Vikings' (p. 24)
	Sept.	2-3	6.70 6.90	8 6	4.40	7	1.87	12	
		11	6.69	4	-	-	1.67	4½	
		16-6	6.83 6.75	5 3½	4.26 4.25	3 4½	1.86 1.86	8 7½	
1942 †	May	19			4.70				
		24			5.00		1.77		
	June	8-9			5.00		1.86		'Sangkalihat' (p. 25)

* Very pure seiches; periods accurately determined.

† Lea gauge marigrams for 1942 were overdamped owing to a blockage in the float well, and results are unreliable.

Table II (contd.):

1943	July	1			4.16*	6	1.82	5	'Compiegne' & 'Marit II'(p.27) Stub-berths.
		25	6.40	2	4.30 4.21	2 3	1.75	3	
		27	5.86	2	4.31*	3	1.87	5	
	Sept.	15	-	-	4.38*	5	1.86	9	
	Oct.	4	-	-	4.67	5	-	-	
1944	May	1	-	-	4.28	6	1.80	7½	
		12	-	-	4.38	3	-	-	
	June	5-6	-	-	4.29	4½	1.75	4½	
		22	-	-	4.00	3	1.86	6	
		28	-	-	4.50	4	1.87	6	
	July	18	-	-	4.14	4½	1.75	4	
	Aug.	9	-	-	4.29*	4	1.82	5	
		30	-	-	4.62	4½	1.77	5	
	Nov.	6	-	-	4.34	7	1.67	6	
		8	-	-	4.31	6	1.76	9	
		18	5.90	4½	4.43	4½	1.82	7	
	Dec.	3	-	-	4.22 4.33 4.64	6 6 6	1.63	8	
1945	May	18	-	-	4.26	2	1.67	3	
		29	5.93 5.54	2 3	4.32 4.07	3 4½	1.84 1.87	7½ 4½	'Egorlock' at J & 'Kosciuszko' at H-berths bumping.
	June	1	5.67 5.05	3 2½	-	-	-	-	
		3-4	5.89 6.00 5.72	3 1 2	4.30 4.29 4.34	2 1½ 1½	1.78	3	Cofferdam at entrance Sturrock Graving Dock in process of being removed
		6	-	-	4.13	3	1.77	3	
		9	5.50 5.45	4½ 3	3.88 4.07	2½ 1½	1.81	4	
		19-20	5.56 5.30	3 4½	3.87	3	1.87 1.77	6 6	
		21-2	5.13	3	-	-	1.87	5	
		23-4	5.66 5.68 5.60	4 4½ 4½	-	-	1.82	4½	

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* Very pure seiches; periods accurately determined.

Table II (contd.)*:

1945	July	5-8	5.31 5.57 5.62 5.64	3 6½ 5 4½	-	-	1.85 1.75	6 7½	'Dahlia' at C berth bumping badly.
		20-1	5.36 5.60	3 2	-	-	1.81	3½	
		25	5.58 5.55	3 3	-	-	1.77	4	
		31	5.55 5.63	4½ 3	3.72	2	1.76	4½	'Anna Howard Shaw'(p.27) at D-berth.
	Aug.	12-3	5.40 5.29	3 4½	3.69	4½	1.76 1.78	8 4½	'Clan Macaulay' at B & 'W.E. Christiansen' at E berth (p. 27)
		15-6	6.00 5.60 5.64 5.20 5.58	3 6 3 6 4½	-	-	1.78 1.83	4½ 2½	
		18-9	5.40 5.61 5.41 5.64	3½ 4 5 4	3.94	3	1.87 1.78	3 9	
		20-1	5.25 5.67	2 4	3.67	2	1.78 1.88	4½ 6	
	Nov.	8	5.57 5.60 5.58	4½ 3 5	-	-	1.72 1.76	5 4½	
		14-5	5.68 5.60 5.25	3 7 4½	3.75	2	1.88 1.88	6 3	
		24	5.40 5.46	3 3	-	-	1.83	4½	
		26	5.35	3	-	-	1.83	5	
	Dec.	7-8	5.43 5.44	5½ 5	-	-	1.78 1.77	4 7½	'King Stephen' (p. 27) at D berth.
		16-7	5.65	3	-	-	1.72	6½	
		26-7	5.60 5.59	2 3½	-	-	1.82	5½	

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* The reader should be cautioned against believing that the number of incidences of Range recorded in this table is an indication of the frequency of occurrence of the phenomenon. The tabulated instances are only representative, and numerous occurrences have not been recorded here at all.

This table records two longitudinal seiches of rather widely different periodicities, which may seem incomprehensible. For a long time this fact was not understood by the author until he realized that the lung of water enclosed by the reclamation works, during construction of the Duncan Dock, was a factor in the situation. During 1940 and 1941 and body of water sealed off from the bay by the Eastern Mole had something of the shape of a clover-leaf (Fig. 10). The shorter-period oscillation of the two longitudinal seiches tabulated was the particular mode resulting from the simultaneous flapping of the three petals of the clover-leaf in opposition to a rise-and-fall of the stem or junction point, in the vicinity of what were later to be J and K berths.

Table II needs to be read in conjunction with the diagrams of Fig. 10, from which it will be noticed that the main longitudinal oscillation had a very much longer period in 1940-41 than subsequently, in conformity with the greater length of the basin in those years. The persistence of the 4.3 minute (average) seiche even after the sealing off of the reclamation-lagoon in the 1944 period is matter for further examination by analytical means. It is curious, too, that in 1944 there should have been an almost entire absence of the main longitudinal seiche, which, however, re-asserted itself in 1945.

The secondary-longitudinal, or diagonal, seiche obviously underwent a radical change from about the middle of June, 1945, onwards, from which time it became very sporadic in occurrence. Its periodicity, it will be noticed, fell to almost the exact double of the transverse seiche, a circumstance, which, as we shall see later, accords with a mode of oscillation of the mass of water just opposite the entrance of the Duncan Basin, in which the node lies in the entrance.

The periodicities of the transverse oscillation between A and E berths are the only ones to remain constant (within limits) over the years, but the range of this oscillation was obviously considerably reduced by the reduction of the entrance-width from 750 to 400 feet in 1940 (cf. p. 21). The greatest range thereafter in the worst year of 1941 was only 2/3 of what it had been. In the years after 1942 the magnitude of the transverse seiche fell away considerably to the extent of a further 25%, but this was undoubtedly due to changes in the weather rather than influences from the far-end of the dock.

A point of significance to which we would call attention, is the absence, on occasion, of one or other of the possible modes of oscillation. On August 10, 1940, for example, the main longitudinal seiche was absent, whereas on August 9, 1941, it was the only one present. All this subscribes to the conception of wave-trains being the cause of excitation, from which trains at different times one or other of the stimulating ground-swells are absent or subdued.

47. Reproductions of Lea-gauge Marigrams.

The value of the Lea-gauge marigrams as an index of the Range conditions increased in proportion as the mystery of the Range phenomenon was unravelled. The author became entirely dependent upon them to know when to set out the portable seichometers and when to make an inspection of the harbour. While the seichometers served the very useful purpose of determining what types of oscillations were simultaneously in existence in various parts of the harbour, both inside and out, they had usually to be placed in operation when it was known that Range had already developed, and seldom in anticipation of the disturbances. The Lea-gauge, on the other hand, while less sensitive, was particularly valuable in that it provided an unbroken record of the sequence of any occurrence of Range-action, and also a means of examining conditions in the past, as exampled in Table II.

Typical examples of Lea-gauge marigrams, from which some of the data of Table II was extracted, are given in Figs. 30 to 42. The obvious reduction in the overall magnitude of the embroidery consequent on the narrowing of the Duncan Basin entrance is noticeable when Figs. 30 and 31 of the 1940 period are compared with Figs. 32 to 42. Fig. 40 shows relatively small oscillations, in spite of which the 'Anna Howard Shaw' at D-berth, not far from the Lea-gauge, broke her stern moorings as described in Section 6 (p. 27): this happened on the night of July 30th, 1945, when the embroidery on the marigram was particularly dense, and therefore suggestive of even shorter-period oscillations than the normal 1.8 minute transverse seiche. Figs. 30, 32, and 33 may also be related to shipping troubles as shown in Table II and described in Section 6. Fig. 34 represents the conditions prevailing during the early hours of September 15th, 1943,--the day on which the aerial photographs were taken (p. 78). Figs. 36 to 39 prove that Range action is not necessarily a feature only of the winter months: local storm conditions were entirely absent on all these occasions.

Still other examples of marigrams on Range-occasions will be given when we come to consider the question of the origin of Range.

48. The Records of the Seichometers.

The individual seichograms of the type of Fig. 20, obtained from the seven portable seichometers, were synchronised by plotting their traces on a common diagram as in Figs. 43 to 53. A very large number of additional records were obtained, especially during the years 1943 and 1944, but owing to lack of adequate assistance it was found impossible to reduce them all. Figs. 43 to 53 represent perhaps the best of the seichograms secured and will serve to illustrate the types of conditions that can prevail.

In each of these figures a small inset diagram reflects the general meteorological conditions existing over a period of days immediately preceding, following and overlapping the day upon which the seichograms were obtained. It will be noted, as we have remarked before, that in nearly every case an obvious barometric depression precedes or accompanies the disturbances.

Figs. 43 and 44 invite comparison. Although recordings for stations 11 and 17 are the only two common to these two charts, there is nevertheless an obvious difference in the traces, which in Fig. 44 are completely lacking the finer frills. Figs. 45 and 46 can be compared in the same way. If there is any essential difference that we can note between the meteorological conditions accompanying these manifestations, it is that the wind was of low velocity and blowing steadily with a minimum of fluctuation on the two occasions when the high-frequency oscillations were absent, whereas its fluctuations covered a fairly wide range on the other two occasions when the oscillations were present. This seems to confirm Chrystal's finding of the dependence of lake-vibrations upon the wind (p. 92), but we shall not at this stage draw any conclusion about this, and shall leave the subject to more exacting scrutiny further on.

Figs. 44 and 46 are particularly interesting insofar as they show the underlying long-period seiches which tend to exist in the oscillating area immediately outside the harbour-basins. Fig. 44 gives the rise-and-fall of water at seven stations along the outside of the Victoria Basin and the Eastern Mole, defining one boundary of the quasi-oscillating basin contained between the breakwater and the shore (Fig. 4). The seichograms for stations 1 and 19, at opposite ends of this oscillating basin reveal some shorter-period undulations than are apparent in the traces at stations 11 and 15. Although they are frequently interfered with by the longer-period undulations, nevertheless their periodicity can be inferred as being of the order of 10½ or 11 minutes. If we examine the relative phase of these oscillations at stations 1 and 19 we find that they are exactly opposed, the water falling at one station when it is rising at the other. This, coupled with the fact that the undulations diminish in magnitude in the traces of the intervening stations, establishes them as being the uninodal seiche between the breakwater and the shore.

Since the mouth of the Victoria Basin lies at the antinode or loop-end of the 11 minute seiche, we are at once enlightened as to the cause of the surge of this periodicity which is so constant a feature of the Alfred Basin (p. 65). the 5½-minute surge in the Alfred Basin follows, á priori, as the second harmonic of the 11-minute seiche, activated by the 5½ minute bi-nodal seiche between the breakwater and the shore, when it is present. As was observed in the weather-tide charts, the 5½-minute surge in the Alfred Basin assumes dominance over its 11-minute parent during storm-periods (p.65), and if we look for the 5½ minute seiche at station 1 in such weather, as for example in Fig. 43 or 45, we find that it is indeed there.

What we have said above in regard to Fig. 44 will be found to be true also of Fig. 46. Certain undulations of period longer than 11 minutes will be found to be common to all the traces of Figs. 44 and 46, and these obviously are seiches connected with some mode of oscillation of Table Bay as a whole, into which we must enquire later. These long-period seiches, we may remark, are present also in Figs. 43 and 45 as may be descried from the mean dash-line superimposed on the trace for station 19 in Fig. 45.

Examination of seichograms 12 and 18 in Fig. 47 shows opposed oscillations of about 4½ minutes period, while at station 16, in-between, its amplitude is small, though showing a phase in synchronism with station 18. Clearly, therefore, we have evidence once again of the existence of a seiche, this time a longitudinal one for the Duncan Basin, (cf. p. 133).

Again, if we inspect seichograms A, C and E of Figs. 51, 52 and 53, the presence of the transverse seiche of about 1.7 minutes periodicity is immediately discovered, in the same way, by the opposed rise and fall of water at A and E berths, and the obvious node in between.

49. Long-Period Seiches and Seismic Sea-Waves.

The long-period seiches of Figs. 44 and 46 are apt on rare occasions to assume very large amplitudes as on October 1st, 1944, (Fig. 48). This phenomenon, which occurs usually in fine weather, was first noticed on November 22nd and 27th, 1943, and at once led the author to enquire into the possibilities of a seismic origin for the disturbances, as in Section 33, (p. 94). The development of a considerable earthquake in Turkey on November 29th, 1943, lent credence to the belief that a submarine disturbance remote from Turkey had preceded the earthquake and given rise to seismic sea-waves, which had drawn from Table Bay a response (Fig. 54) not wholly dissimilar to that occasioned by the Krakatoa eruption of 1883. The fact that the latter eruption gave rise to air-waves lent further support to this belief, because fluctuations were observed on the barograms for both November 22nd and 27th, 1943. The author considered the possibility of these fluctuations being the cause of the seiches but abandoned the idea after it was found that there was no evidence of the Krakatoa push-pull air-waves having induced seiches in Table Bay (p. 99): (he had not at this stage examined the evidence of gravity air-waves from the Lisbon earthquake of 1755, which pointed in the other direction).

To discover, if possible, the epicentre of the supposed seismic sea-waves, the marigrams of the Port Elizabeth tide-gauge were obtained for comparison with Cape Town's. The tide-curve at Port Elizabeth for November 27th was normal, but showed corresponding long-period oscillations on November 21-23, 1943. However, the definition of these was not sufficient to enable any deduction to be made.

Further occurrences of large-amplitude, long-period seiches in Table Bay on August 12-13th, and September 10th, 1944, (Figs. 55 and 56) re-opened this investigation. These phenomena caused violent surging of the water through the entrance of the Duncan Basin at velocities estimated to be of the order of 4 or 5 knots, and on September 10th the current eventually tore from its moorings the anti-submarine boom-defence. Once again these long seiches occurred in fine weather, and Figs. 55 and 56 are seen to be free of most of the short-period scalloping.

The marigrams from Port Elizabeth on these occasions showed an unmistakable correlation with those of Cape Town. Whereas at Cape Town the periodicities of the long-period seiches were of the order of 58, 33 and 16½ minutes, and the amplitudes about 15 inches, at Port Elizabeth the periodicities were approximately 55, 28 and 15 minutes, and the amplitudes about 12 inches. The disturbance of August 12th, however, reached its peak at Port Elizabeth some 18 hours before that at Cape Town, while the disturbance of September 10th occurred at Cape Town about 13 hours earlier than at Port Elizabeth.

If the seiches were caused by seismic sea-waves we would expect to find the epicentre of August 12th somewhere east of Port Elizabeth, in which case the waves would have to travel the extra 450 odd miles between the two ports to reach Cape Town, after Port Elizabeth. Even if we took the worst case and assumed that the waves were obliged to travel in water under 600 feet in depth at an average speed of only 50 mph, (Fig. 27), it would take them but 9 hours to cover the distance, and another 9 hours would remain to be accounted for in the time difference of arrivals at the two ports. Our first impulse on noting this discrepancy might be to think that we had forgotten about the group-velocity of waves, but long waves are not subject to any reduction in speed even when travelling in groups, as discussed in Section 38, (p. 112), and the disparity remains.

The conception of seismic sea-waves becomes equally untenable when looked at from the occurrence of September 10th, 1944, which would have to have an origin somewhere west of Cape Town. The same argument applies in this reverse direction, and the time-difference between the arrivals of seismic sea-waves at the two ports could not exceed 9 hours, and would definitely be still less if the epicentric origin were anywhere south of the common latitude of the two places.

These considerations thus exploded the idea of a common seismic origin for these phenomenal seiches, and led to a re-examination of the meteorological conditions. In this the Port Elizabeth barograms played an important rôle, for both the time and pressure scales of the recording instrument were sufficiently open to make it sensitive to comparatively small pressure-variations. Careful inspection of these barograms at once revealed an embroidery indicative of the presence of air-waves on just those occsions when long-period sea-oscillations were induced at Port Elizabeth. In particular, when the air-waves were compared with the sea-oscillations of August 12th, it was found that the latter responded in general to the tendencies of the air-waves, as is clearly revealed in Fig. 56: moreover, the apparent periodicities of the air-waves closely conformed with the 15, 28 and 55 minute periodicities of the sea-seiches. This illuminating discovery was immediately followed by the recognition of similar oscillations in the atmosphere exhibited in the less-sensitive barograms for Cape Town - fluctuations which had all but escaped notice because of the crowded scale of our instrument. Fig. 56 shows the air-pressure curves for Port Elizabeth and Cape Town, the latter's being the best reproduction that could be made from the fore-shortened scales of the instrument. Had the Cape Town barograph been more sensitive it is probable that it would have revealed undulations very similar to those of Port Elizabeth. Further inspection of the barograms for November 22nd and 28th, 1943, confirmed in an unmistakable way that whenever there were prominent long-period seiches there were also accompanying barometric fluctuations.

Close on the heels of these revelations came the long seiches of October 1st, 1944, Figs. 48 and 57. Here again periodicities were of the order of 58, 33 and 17 minutes and air oscillations were in attendance. Water was observed to be surging through the Duncan Basin entrance at velocities approaching 5 knots, but ships at their berths were entirely unaffected except insofar as they rose and fell slowly with the flood and ebb in the docks. The rush of water through the entrances could have been extremely dangerous to large vessels in motion: fortunately, there was not much shipping activity in the docks at the time, but the author observed a yacht caught in the ebb-flood at the mouth of the Duncan Basin, in which it was whirled round like a cork before it could extricate itself.

We give finally in Fig. 58 the Lea and Lege-gauge marigrams for April 8-9th, 1945, and the simultaneous barogram, which portrays more convincingly than we can express in words the genesis of long-period seiches as a result of oscillations in the atmosphere. The first, sharp pressure-rise at 6.30 p.m. was like a plunger on the water-surface of Table Bay which set in motion seiches of apparent periodicities 61, 45, 34, 25 and 20 minutes, three of which are closely similar to periodicities mentioned before. The 'plunger' descended again just as the seiche was welling up at the harbour-end of the bay at 8.15 p.m, and the seiche appears to have been promptly damped, although approximate 20 minute air-waves between 8.15 and 9.15 stimulated the corresponding 20 minute seiche in the bay. At 10.0 p.m. a sudden lifting of the pressure, followed half-an-hour later by the drop of the 'plunger' again, set in motion once more the 34-minute seiche, and the ensuing upward and downward strokes of the 'plunger' were timed so well as to induce large oscillations of water in the bay. After about 2.30 a.m. the barometric disturbance died away and the seiches damped out.

50. The Dangers of Surging at Basin-Entrances.

The author commenced a search in the Lea-gauge marigrams of previous years for further information on these seiches and at once uncovered a fact which drew attention to the inherent dangers involved, during these spells, in the navigation of ships through the basin-entrances. Fig. 59 is the marigram for October 8th,,1942, the day on which the difficulties described in Section 6 (p. 26) were experienced, from which it will be seen that large-amplitude oscillations were in evidence at precisely the times that the 'Canton' and 'Bankok' incidents occurred in the entrance of the Duncan Basin. We give below the report of Capt. Hodges, the pilot responsible for docking the 'City of Canton'*, which speaks for itself:

> " I have to report the following extraordinary incident whilst docking this vessel of 6690 tons gross, on a draft of 26 ft. 4 ins. I boarded this vessel at anchor at 8 a.m. and got under way. Coming up to the New Dock entrance I followed H.M.S. Tunmoor at a distance of about 1000 ft., reducing speed as required so as not to overtake. A strong tide rip was noticeable both in and outside the entrance. We appeared to just feel its influence at 8.25, when I found the vessel inclined not to obey her helm (say 1200 ft. from the entrance).
>
> " At 8.28 the tug T.H.Watermeyer came alongside and we proceeded at about 3 knots. At 8.34 observing to the Captain of the ship that she had been brought practically to a standstill, I gave the order Full Ahead, which the Captain repeated and gave 'All Out', the ship however came to a stop, (the engines were turbines and took time to develop their power), and then gathered sternway at the same time falling bodily towards the North bullnose, until within 12 feet, when I brought the helm to midships from hard-a-starboard, and stopped the engines, allowing the ship to drift. The tide now caught our starboard

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* Port Captain's official papers P.C./A/306, October 12th, 1942.

> bow and threw it to port, the ship moving astern at a good pace (5/6 knots) her stern swinging towards the Boom mooring buoy (on the North side). To clear it I ordered Full-Ahead again at 8.38, and when the ship had lost sternway, stopped the engines. She drifted a full 1200 feet from the entrance under the influence of the tide.
>
> " Making up to the entrance a second time at Full Speed and stopping inside, the tide influenced the steering more than halfway across the dock.
>
> " Low water was at 8 a.m."

The serious nature of these incidents requires no emphasis and yet there have been remarkably few mishaps, very largely, it seems, owing to sheer good-luck. The occurrences of August 12th, September 10th and October 1st, 1944, (Figs. 55, 56 and 57) were all of greater magnitude than that of October 8th, 1942, and could therefore have been expected to produce even more violent surges, yet, because they came at times when there was very little shipping in the harbour, they passed almost unnoticed.

Reference again to Fig. 48 shows that at stations 11, 14, 16 and 18 in the Duncan Basin there was virtually a simultaneous and equal rise-and-fall of water between 10.40 and 11.15 a.m. on October 1st, 1944. This could only mean that the whole area of the dock increased its depth by some 30 inches in the interval of time between 10.55 and 11.05, necessitating an addition of water of 30 x 10^6 cu. ft. in 10 minutes. This enormous volume had to gain admittance through an entrance only 400 ft. wide by 43 ft. deep and its average velocity of inrush would therefore have been about 3 ft./sec. Owing to the slow movement at the reversals of flow, preceding and following the rise of level, the maximum velocity through the entrance would be greater than this figure in the proportion (about 1.8) that the steepest gradient of the seichograms exceeds the mean gradient between the times quoted. The probable, maximum speed of influx was therefore of the order of 5½ ft./sec., or about 4 mph, which largely substantiates the visual estimate of 5 knots (p. 145). ?

Since current velocities in the entrances of different basins will be proportional to the ratios of the surface-areas

$7.5 (\times 10^2)$, that the respective velocities of flow are approximately as 1:1½:4. Conditions which produce a 4-knot current through the Duncan Basin entrance, thus induce only 1 and 1½-knot currents at the mouths of the Alfred and Victoria Basins.

The author has now seen several instances of these long-period seiches and found the phenomenon both fascinating and awesome to watch. Water rushes through the Duncan Basin entrance in a veritable torrent that whirls and eddies almost half-a-mile out into the bay and nearly to the opposite side of the basin. The commotion fans out beyond the entrance and the sea appears to churn and boil in the distance long after the current in the entrance has ceased to flow and begun to reverse.

It should be pointed out that there is only danger from these long-period seiches if a ship happens to be negotiating an entrance at the time that the seiches (usually three, of periodicities, 56-61, 27-33, and 15-21 minutes) coalesce to produce a large oscillation. This is rather unpredictable, but owing to the long periods over which these seiches are often active, (sometimes two or three days), the chance that a ship will be caught in difficulties is always there, and is relatively a big one.

51. The Frequency of Occurrence and Magnitude of Long-Period Seiches.

The record of occurrences of prominent long-period seiches as extracted from the Lea-gauge marigrams is given below in Table III, for the period 1940 to 1946: Some of the data for this table is lacking, but as a frequency indication

Table III: Principal Long-Period Oscillations in Duncan Basin, 1940-1946.

Year	Month	Day	Range (2A) of Seiches ins.	Ships affected & Remarks.
1940	Aug.	3-4	Large	
		17-19	Moderate	
	Sept.	10-12	Very Large	
	Oct.	29	20	
1941	Jan.	18-19	15	Very short duration
	Mar.	7-8	10	
	Aug.	12	16	
1942	Oct.	8	10 1/2	Tug 'Buffalo' & HMS.'Spindrift' collide,Vict.Basn.: 'Canton'&'Bankok'narrow shaves,Duncan Bas.,(P.50).
1943	June	30	11	2 Minesweepers adrift from Alfred Basin.
	Sept.	10	12	
		19-20	14	
		27	16	
		30	14	
	Nov.	22	13 1/2	
		27-28	18	
1944	Jan.	12	13 1/2	
	Aug.	12-13	32	
		28-29	12	
	Sept.	10	31 1/2	Boom defence torn from moorings, Duncan Basin
	Oct.	1- 3	32	
		10	11	
1945	Aprl.	8- 9	21	
	May	11	Slight	
		19	13	
	June	21	Moderate	Short-period seiches superimposed.
	July	23-25	18	Ditto.
	Aug.	2- 4	Moderate	
		7	Moderate	Very short duration.
		9-10	Moderate	Very short duration.
	Sept.	24-25	24	'Samnegros' deflected. Duncan Basin.
		30- 1	18	'Red Jacket'in difficulties,Victoria Basin.
	Oct.	8-10	Slight	
		25	Slight	
		28-29	Slight	
	Dec.	12-13	15	
		21	Slight	

1946	Mar.	17-18	14	Short-period seiches superimposed
		28	28	
	Aprl.	3	Moderate	
		26	Moderate	
	May	9-10	Moderate	
	June	2- 3	Slight	
		4	Moderate	Short-period seiches superimposed.
		24-25	Large	
	Aug.	21-22	Large	
	Sept.	2	14	

of the phenomenon it is fairly reliable. The remarkable thing is that the years 1940 to 1942, which were very bad from the Range point of view, produced so few incursions of long seiches; in contradistinction, the years 1943 to 1946, which were lean in bringing serious Range troubles, show a greater frequency of long seiches. Whether any significance can be attached to this rather discrete observation will have to be considered in a later chapter. It would appear, however, that the dangerous conditions we have drawn attention to are likely to arise at least two or three times in a year.

52. The Dual Character of Range-Action.

On the basis that there is a uniform rise or fall of water through a range $2A$ in the time $\tau/2$, (the half-period of the seiche), over the entire area of a dock, the velocity of flow through the entrance will be

$$V = C.(4A/\tau), \qquad \text{\_\_\_\_\_\_\_\_}(13).$$

where C is the ratio of the surface-area of the basin to the sectional area of its opening.

If we consider seiches of the same magnitude, ($2A$), but different periodicities, (τ), in the Alfred, Victoria and Duncan Basins, such that the velocities, (V), induced in their entrances are all equal, then it follows from (13) that the periodicities must be in the proportion of the ratios C, which, as we have seen (p. 148), are respectively as 1:1½:4. Hence, if a long-period seiche of 18-minutes period can induce, say, a 4-knot current through the Duncan Basin entrance, equal currents can only be produced in the Alfred and Victoria Basin entrances, if the exciting seiches are respectively of periodicities 4½ and 6¾ minutes, which may be considered within the sphere of short-period oscillations.

While we recognize from this that Run in the smaller basins can be just as powerful as in the Duncan Basin, according to the periodicity of seiche prevailing, it reverses more rapidly and is not such a sustained millrace as in the latter basin.

Comparison of Tables II and III shows that the only occasions on which short-period seiches occurred simultaneously with prominent long-period seiches were the few remarked upon in Table III, in all of which cases the high-frequency effects were minor. This peculiar estrangement gives to the Range problem a dual personality, which we may define as a division between large-amplitude, long-period seiches on the one hand, and large-amplitude, short-period seiches on the other. The first phenomenon produces very powerful and prolonged fluxes of water through the Duncan Basin entrance, which are dangerous to ship-navigation, but creates no trouble at the quays; the second produces short, powerful fluxes through the Victoria and Alfred Basin entrances, and is characterised by the troublesome motion it communicates to ships at their berths in all the basins.

The curious feature that these 'Jekyll and Hyde' aspects of Range-action rarely occur together in severe form is noteworthy. Although long seiches are usually present during short-period Range-action, as we have noted in Section 48 (p. 141), they are nevertheless invariably subdued; and when they do assume the large proportions of Figs. 48 and 54 to 58, it is usually at a time when short-period seiches are quiescent. The implications of this observation must be reserved for later study, while we pursue the story of further findings.

53. The Measurement of Barometric Oscillations.

Following upon the discovery in October, 1944, of the undoubted relationship between long-period seiches and barometric oscillations, steps were immediately taken to increase the sensitivity of the barometric recording instrument. The more sensitive Port Elizabeth barograph was acquired in place of the original one, and the author also seriously contemplated requisitioning for a Dines-Shaw Microbarograph. The difficulties of war-time supply, however, precluded anything being done in this direction, and consideration was then given to the construction of a statoscope similar to that devised by Professor Chrystal*, whose work by this time had been consulted. The statoscope was a converted recording barograph in which the pressure-capsules were open to the atmosphere and able to expand or contract against the fixed pressure of a surrounding sealed air-container.

From this the idea was gained of using the same principle in a system of manometer tubes. After considerable experiment and some frustration an entirely satisfactory recording microbarograph was evolved at no greater expense than the employment of a broken glass manometer and the acquisition of a wide-mouthed bottle of some 2 ins. internal diameter. The device is illustrated in Figs. 60 and 61, and depends for its operation on pressure-and-volume changes in air, according to Boyle's Law. As it was important to insulate the air-volumes against changes of temperature the main manometer was jacketed in an old ice-cream freezer and the connections to the secondary manometer

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* 'Investigation of Seiches of Loch Earn by the Scottish Loch Survey', Trans. Roy.Soc.Edinb., Vol.45, Part II, 1906, [84], pp. 361-396.

were heavily lagged with asbestos. A float, riding in the small limb of the secondary manometer, actuated a lever-pen which scribed on smoked paper on an electrical-kymograph drum.

Results from this instrument exceeded the most sanguine expectations: it proved capable of registering minute variations of pressure, and individual fluctuations could be identified on the very open time-scale which the kymograph provided. Typical examples of the microbarograms obtained are given in Figs. 62 to 70: these will be referred to in detail in the next part of this work when the meteorological conditions surrounding the development of Range-action are more closely studied.

Fig. 70 has been included as an item of interest concerning the Bikini-Atoll atom-bomb test of July 1st, 1946. It was thought possible that the bomb-blast might set up an air-pressure wave strong enough to make itself felt at Cape Town, in much the same way as the Krakatoa eruption had given rise to air-waves, and the microbarograph was accordingly set in operation on the due date. The microbarogram of Fig. 70 confirmed the ordinary barograph in showing that a drop of about 0.07 inch of mercury occurred suddenly after noon of that day, almost exactly 12½ hours after the explosion had taken place. Whether this was actually an indication of the passage of an air-wave cannot be known for certain, but it is significant that the pressure drop occurred at about the time that an air-wave would have been expected from Bikini, some 9870 miles away (measured along a great circle). The calculated speed of the wave to have covered this distance in 12½ hours is about 790 mph, which is of the expected order, although on the high side. The microbarograph also registered a sudden, but small, pressure rise at 18.12 hours the same day, at roughly the time that a return wave could have been expected from the antipodes of Bikini, (about

2590 miles from Cape Town). A certain amount of long-period seiche-disturbance in Table Bay was apparent at the time, but, owing to a concurrence of ordinary Range-action, it could not be associated with the barometric fluctuation.

PART III

METHODOLOGICAL AND OTHER ORIGINS OF RANGE

" They (hypotheses) should be regarded as instruments by which new lines of inquiry are indicated; or by the aid of which a provisional coherency and intelligibility may be given to seemingly disconnected groups of phenomena."

—— Thomas Huxley

CHAPTER VIII.

TRAVELLING DEPRESSIONS OF THE SOUTH ATLANTIC.

> "Hen scarts and filly tails*
> Make lofty ships wear low sails."
>
> — Old Saying (Scottish Origin).

54. Invocation of Further Meteorological Data.

The obvious association between Range and barometric depressions in the records of the phenomenon at Cape Town has already been remarked upon (pp. 65 and 140). The quest for further information on this relationship, which literature has indicated involves the cyclonic storms of the open oceans (cf. pp. 86, 101, 120), led the author to consult the Chief Naval Meteorological Officer†, (South Atlantic), early in 1943. This Officer was able to furnish important information in the form of synoptic charts for the South Atlantic region, indicating the movements of travelling depressions: he suggested further, as we shall later consider, the dependence of Range upon the arrival of the cold-fronts of these depressions, a conclusion reached on the basis of the weather-tide charts for 1941, 1942 and 1943 which were submitted to him for scrutiny and comparison with his more extensive data.

We are at once led to enquire further into the nature of these travelling depressions. For their understanding it will be necessary to refer to the hemispherical circulation of the atmosphere, in somewhat greater detail than was considered appropriate to Section 8, (p. 32).

55. Movements of the Atmosphere in the Southern Hemisphere.

It is logical to suppose that an atmospheric shell

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* High-altitude Cirrus clouds resembling the spread claws of a hen and the tails of young mares: usually the forerunners of a storm.

† Commander V.A.Bishop; succeeded in 1944 by Commander H.S.Gracie.

enveloping a spinning sphere would, as a result of its viscosity, turbulence and friction, steadily slip backwards relative to the sphere, although it would acquire some of the angular momentum and would rotate in the same direction. In the case of the earth, if we could assume no north and south movement in the atmospheric shell, we should thus expect steady winds from east to west with a maximum velocity at the equator tapering to zero at the poles; such winds would be only slight on the surface of the earth, where slip would be small, but would gain in velocity with elevation.

However, these natural tendencies are overshadowed by the influence of solar radiation and heat from the earth's surface which are all important in setting up north-south convection currents, necessary to effect heat exchanges in the atmosphere. Cold air, moving towards the equator from the poles thus becomes subject to the laws of rotation and is pulled westwards off its direct course, through having a lower angular momentum than is required for the latitudes over which it has to pass. Between latitudes 30°N and 30°S the actual surface winds are precisely in accordance with this concept and constitute the familiar north-east and south-east trade-winds of the northern and southern hemispheres respectively.

The polar air engaged in this mass-movement requires, of course, constant replenishment, which can only be furnished by the return of warm air from the equator at higher levels. This air, in moving from the equator, has greater angular momentum than is necessary to the latitudes which it must traverse, and in rotating faster than the earth, is therefore swung westwards.

If the terminals of this movement were actually at the poles, the surface winds near the equator and the upper-air movements at the poles could be expected to attain such tremendous velocities, through accumulated angular momentum, that turbulence and frictional drag on the earth would be vastly greater than they are, and life such as we know it might not be possible on the face of this globe*. There would be the difficulty, too, of finding accommodation at the poles for the volume of air flooding back from the equator.

Characteristically, Nature has sought the path of least resistance and placed the effective terminals of movement, not at the poles, but in the regions of latitudes 30°N and 30°S, where lie, as we have noted in Fig. 6, the high-pressure doldrums of calm air or light winds. Air in these regions thus has about the same peripheral velocity as the earth's surface. Equatorward, the atmosphere rotates more slowly than the earth and therefore slips towards the west, while, poleward, the air rotates more rapidly and accordingly blows towards the east.

Since the movement of air is promoted gravitationally by flow from high to low pressure, the necessary condition for the existence of these terminals is a high-pressure belt. In the southern hemisphere, as we see from Fig. 6, the high-pressure belt necessary to generate the surface-winds is in existence throughout the year, merely varying as to intensity with the change of seasons. At altitudes of 10,000 feet and more, however, this system of isobars changes and the highest pressures are at the equator, as required to cause the feed-back of air to the temperate latitudes.

The directions of flow of air from the high-pressure belt, Fig. 6 (westward to the north , and eastward to the south), have been epitomised in Buys Ballots rule (for the southern hemisphere), that higher pressure is on your left when you stand with your back to the wind.

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* This problem was investigated by Helmholtz in his work 'Uber Atmospharische Bewegungen', 1888, who concluded that mixing of differently moving strata of air by means of whirls that originate in the unrolling of surfaces of discontinuity, was the principal agent preventing the development of more violent winds. Cf. Napier Shaw,(l.c.ante, p.39),[32], Vol. IV., p. 61.

The geostrophic wind-speed, corresponding to the pressure gradient across the isobars, is greatest to the south of the high-pressure belt, as may be judged from the crowding of the isobars towards the south-pole (Fig. 6). A great whirl of west winds, famous as the 'roaring forties', is continuous here on a small circle round the south pole, and within this region lies the polar front, where warm air from the equator, flooding in from high levels or peeling off from the high-pressure doldrums, encounters the cold polar air-mass. It is along this front that travelling depressions form as gigantic eddies in the atmosphere, created by the relative incompatibility of two masses of air, flowing across each other at different speeds.

56. The Genesis of Frontal Depressions.

The essential features of a travelling, revolving storm have long been known and were formulated in Dove's law of storms of 1828 and the subsequent embellishments of it by Redfield, Reid and Piddington up to 1855[*]. But the modern conception of the cyclonic storm of the temperate latitudes really dates from Sir Napier Shaw's recognition of the composite features of a depression, and the crystallisation given to these ideas by the Norwegian Meteorologists J. Bjerknes and Solberg in 1918[†].

According to Bjerknes, the polar-front discontinuity between cold air from the poles and warm air from the equator, moving across each other at different velocities, is periodically disrupted by the formation of cyclonic depressions, which are the means of effecting heat exchanges in the most rapid way possible.

The life-cycle of a typical depression of the southern hemisphere is depicted in Fig. 71, which is adapted from the

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[*] Cf. Napier Shaw: (l.c. ante p. 39), [32], Vol. I, pp. 296-7.
[†] Ibid., [32], Vol. II, pp. 381-398.

illustration given by Bjerknes and Solberg for a depression of the northern hemisphere, and from later information given by Brunt[*].

The original illustration was given for air-masses moving across each other in opposing directions, but in the southern hemisphere, where the polar front exists in the slip-stream of the 'roaring forties', the air masses are obviously flowing in the same direction. According to Brunt this is also the condition under which depressions are most usually born in the northern hemisphere[†]. Fig. 71 has therefore been drawn to represent the condition of concurrent flow.

The stability of the polar front (a), Fig. 71, is upset by a bulge of warm air pressing into the cold air-mass, as in (b). The bulge deepens and a whirl begins to develop, causing a local reversal in the flow of the cold air round the depression centre. Winds blow clockwise round the centre and inwards, spirally, across the isobars, (c). The depression deepens and barometric pressure falls in virtue of a more rapid outflow of air at high altitudes than inflow at the surface.

As it develops the depression moves forward at the speed of the winds of the warm sector and in the direction of the isobars for that area[§]. The warm air is gradually undermined by the closing of the fronts which define its boundaries with the cold air-mass. The warm-sector winds blow strongly from the north-west across the surface of the sea and rise up over the cold air along the warm front of the depression. Westerly and south-westerly winds bore in under the warm air along the cold front, until occlusion occurs, which is marked by the coincidence of the warm and cold fronts. At this stage the warm air has been pushed aloft, except near the northern extremities of the fronts, and the depression begins to lose vitality and finally

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[*] 'Weather Study', (London), 1944, [85], pp. 175-210.
[†] Ibid., [85], p. 173.
[§] Ibid., [85], p. 177.

expends itself in a whirl of air. However, as often happens, the occluded fronts, as shown in (e), form a surface of separation between the preceding and following cold air-masses, which, through acquired differences in properties, are themselves not always miscible, and the front may persist for some time. As diagram (f) shows, a secondary depression may be born out of one that is in process of dying.

Travelling depressions have been found to form in families of from two to four. Their members represent various stages in the life-history of a depression, as depicted in Fig. 71, young ones forming in the rear as the older ones advance and progress towards maturity.

57. Recognizable Features of Fronts.

The characteristic features of a fully developed frontal depression, as it might appear to a high-altitude observer, looking southwards from a vantage point somewhere in the vicinity of St. Helena, are shown in Fig. 72[*].

The warm front is characterised by a sloping bank of cloud produced by the condensation of moisture in the warm air as it rises over the antecedent cold air-mass. The greatest concentration of this cloud is round the depression centre. Feathery cirrus clouds are the harbingers of the storm and are sometimes to be found 500 miles in advance of the warm front at its ground-line. Behind these 'outriggers' follow, in order of decreasing altitude, cirrostratus, altostratus and finally nimbostratus clouds. It must be remarked that the warm fronts of the southern hemisphere are not so well defined as in the northern hemisphere, and these clouds are often absent[†] over the land.

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[*] Based on descriptions of depressions of the northern hemisphere, (l.c. ante p. 160), [85] and [32].

[†] L.c. (ante p. 34), [25].

In the up-draught at the depression centre are to be found towering cloud-castles of nimbostratus, which extend also some distance along the cold front and are preceded by lenticular formations of altocumulus cloud. Warm-sector weather is accompanied by broken cumuliform cloud, rain, drizzle and fog. Rain along the cold front may occur over a belt perhaps 50 miles wide, but usually varies in intensity with the onset of intermittent squalls.

These squalls occur along the edge-shaped surface of separation of the cold front and have been ascribed to an overriding nose of cold air periodically forming and plunging over cold air whose movement has been retarded by contact with the ground*. The opinion will be advanced in the next chapter that these squalls at the cold front are manifestations of breaking air-waves formed, as envisaged by Helmholtz, at the sloping surface of discontinuity and advancing down it until destroyed or expended in the shallowing depths in much the same way as surf is dissipated along a sea-coast.

As indicated in Fig. 72, the isobars have an abrupt discontinuity at the fronts. The same discontinuity is revealed in the wind directions and the advance of the fronts over any particular station can be noted by the backing of the wind to north-west behind the warm front, and then suddenly from north-west to west or south-west with the arrival of the cold front.

Other features by which the passage of a depression may be recognised are the gradual fall and subsequent sudden drop of temperature, marking the arrival and departure of the warm sector air mass; also the steady fall and subsequent rise of the barometer.

At Cape Town an indication of the approach of a

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* Brunt, (l.c.ante p. 160), [85], p. 179.

depression is given by the shifting of the wind from south-east to north-east. Strong north-westerly upper winds override the easterly surface wind and warm weather prevails until the upper winds gradually descend to the surface. Low-lying cloud moves inland accompanied by rain and surface temperature usually falls, instead of rising as might be expected of warm-sector weather. This fact and the absence, usually, of the sloping bank of warm-front clouds, make it difficult sometimes to establish this front*.

As Fig. 73 portrays, the locus of a depression-centre usually bears towards the south-east. The depressions appear to have their infancy in the south-west corner of the high-pressure belt not far from the coast of Brazil. They advance at speeds of about 35 knots and curve round the coast of South Africa at distances not usually less than 500 miles to the south. Small secondary depressions, however, may form within close proximity to the coast. Notwithstanding the remoteness of the depression centres, the long arms of the fronts reach out 1000 or 1500 miles to envelop most of the fringe of South Africa.

58. High-Pressure Anticyclones.

Although in Fig. 6 we have conceived the high-pressure belt of the South Atlantic region to be very stable and subject only to slow seasonal change, it is in point of fact prone to vary almost daily in the intensity and the configuration of its isobars, through being affected by the passage of the travelling depressions. The oceanic belt may split into two or more anti-cyclones or systems of closed isobars which may be stationary or moving, according to whether they are warm or cold†. The cold

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* L.C. (ante p. 34), [25].
† Napier Shaw: (l.c. ante p. 39), [32], Vol. II, p. 400.

anticyclones form behind the travelling depressions with influx of air into regions previously denuded by the propagation of the cyclonic storms.

A feature of depressions and anticyclone at Cape Town is the obvious relationship between mean temperature and pressure, clearly shown in the weather-tide charts of Figs. 14, 15 and 16. As pressure falls, marking the advent of a depression, so mean temperature rises, and as the anticyclone moves in with higher pressure at the rear, mean temperature falls again.

According to the latest findings of hemispherical surveys of the upper air*, in the northern hemisphere at least, it is possible for comparatively warm anticyclonic upper-air masses to invade the polar regions and displace cold air to the middle latitudes, where it forms a ring of cyclonic centres, giving rise to the travelling depressions we have described. These 'polar outbursts' are now current terminology in the meteorological world, and as they vary as to severity and penetration, they are a considerable factor in the modern forecasting of weather.

59. The Association between Range and Frontal Depressions.

We turn now to consider more positively the connection between these meteorological disturbances and the phenomenon of Range of the higher frequency type (cf. Section 52,p.151).

Close scrutiny of Figs. 12 to 16 fails to reveal any single factor that can be identified as an infallible link between Range action and local weather. A few examples may serve to illustrate this statement.

(1). Barometric pressure-sags at Cape Town, although generally indicative of the advance of frontal depressions and of

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* Cf. Rossby: 'Recent Advances and Probable Future Trends in Basic and Applied Meteorology', Proc. 3rd Hydraulics Conference, Univ. of Iowa, June, 1946, [86], pp. 115-120.

the incidence of Range, are not in themselves always a reliable index. Range-action is found to lag behind a pressure-sag in some cases and precede it in others; but instances are quite numerous where Range has developed while barometric pressure at Cape Town has been high. Examples of this will be found in Fig. 13 (July 21, 1942), Fig. 14 (b) (June 1, 1945), and cases are common where Range has been pronounced without the accompaniment of any very obvious depression.

(2). Strong local winds from the north-west are also no dependable criterion for expecting the onset of Range. The occasions which gave rise to the marigrams of Figs. 36, 37 and 38 were nearly all calm and fine, Fig. 14 (a), (November 6, 8, 14, 18, 1944). Fig. 14 (b) (June 1, 1945) likewise shows pronounced Range during a period of absolute calm extending over 3 days.

(3). Although in the more meticulous weather-tide chart for 1947 (Fig. 16) we can observe a clear-cut influence of the semi-diurnal tide upon the transverse oscillations of the Duncan Basin (red dash-lines), this is no more than a slight increase in the amplitude of the oscillations at every high tide - a matter we shall have to concern ourselves with in later analysis. There is, however, no other obvious connection with the tides, and severe Range-action will occur as often at neaps as at springs.

(4). Local mean temperature, as pointed out in the last section, is the inverse of barometric pressure, and we can expect no more from this than we could of barometric pressure.

The Admiralty meteorologists, who had been consulted for further data (p. 156), advanced the theory that heavy north-west gales which are a feature of warm-sector weather in depressions, as we have seen, cause a piling up of relatively warm water at the harbour-end of Table Bay. With the crossing of the cold front the wind then suddenly veers to south-west and blows almost at right angles to its previous direction thus releasing the pent-up water in the Bay. Oscillation of the water in the bay then commenced, they supposed, with the cold Benguela current forming a 'retaining wall' at the node of the oscillation.

In the light of our knowledge of seiche phenomena, there are features of this hypothesis which are obviously unsatisfactory. First and foremost, any oscillation induced under the conditions they infer must necessarily damp out at once, since there is nothing to sustain it. Once the pent-up water were released, it would create a wave which would split on either side of Robben Island and only a fraction of the accumulated energy would be reflected even assuming the 'retaining wall' of cold water were sufficiently elastic to yield to the nodal surge and throw the warm water back into the bay. But there are other objections, among these being the facts that Range is frequently prominent during prevalence of the north-west wind before its change of direction, and also that Range of both the short and the long-period varieties can exist without any local wind at all. It is impossible to believe that short-period Range-action could be induced under the conditions the meteorologists entertain, and long-period seiches in Table Bay as we already know, are infallibly linked with barometric oscillations. We are compelled therefore to conclude that this hypothesis does not sufficiently fit the facts.

60. Cold Fronts in Relation to Range-Action.

The only feature of the above theory which is worthy of close examination is the possible connection between Range and the fronts of an advancing depression. The warm front, owing to its diffuseness and unfavourable inclination when crossing

Cape town, may reasonably be ignored*, but the cold front, defining a sharp discontinuity in pressure, might, in the nature of things, be expected to set up trains of sea-waves both in advance and behind, as it progresses across the ocean towards Cape Town.

Example 1°.

We select as our first example for consideration of such a contingency the occurrences of Range in the summer month of November, 1944, already reflected in the marigrams of Figs. 36, 37 and 38, and the seichograms of Figs. 49 and 50. The general weather conditions prevailing at Cape Town at the time are given in Fig. 14 (a), and the meteorological conditions over the ocean to the west of South Africa are portrayed in the synoptic charts (reproduced from Admiralty records) of Fig. 74.

The synoptic charts of the South Atlantic show the isobars prevailing at 2.30 hours in the morning of successive days from November 3rd to 20th, 1944. The depressions with their warm and cold fronts, in various stages of their life history leading to occlusion, are clearly identifiable, and the trend of their movement is indicated by arrows.

Depression A in Fig. 74 (a) is advancing towards the east, and by the time it has reached the position (b), is being followed by a family of succeeding depressions, B, C and D, whose further progress can be traced in (c), (d) and (e). The parent A has veered south and occluded at time (c), when the upper end of the cold front is just about to cross over Cape Town. Reference to Fig. 14 (a) shows that Range action built up from the time of the crossing of this front over Cape Town in the early hours of November 5th.

Although it is difficult to know for certain, it seems that at stage (d), Fig. 74, depression A had broken up and

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* The justification for this may be verified by the reader on the basis of evidence presented in the examples which follow.

formed the secondary A', no doubt with the remnants of B, which from its state of occlusion in (c) must have fizzled out. Depression D, meanwhile is seen to be closing in on C and has merged with it at (e). In (f) the cold front of CD has crossed over Cape Town, and we find again from Fig. 14 (a) that Range action at Cape Town flaired up to large proportions on November 8th.

Depression E at stage (f), Fig. 74, appears to be running into an anticyclone. Obviously it must have merged with the family to the southward and formed the intense depression F, shown in (g).

In (h) the leading cold front of F has just crossed Cape Town, but reference to Fig. 14 (a) shows this time that there was no response in the form of Range-action.

The progress of the next depression G may be traced in (k), (l) and (m). At (m) a secondary G' seems to have formed out of the occlusion of G, and its cold front must be assumed to have crossed Cape Town at about 14 hours on November 12th, but Fig. 14 (a) again shows no tally with Range-action.

Depression G must have exhausted itself between (m) and (n) just at the time that Range at Cape Town attained large amplitudes in a perfect calm (Fig. 14 (a)) without any frontal crossing at all.

In (o) and (p) the intense depression H apparently headed south-east and was followed up by a strong anticyclone. The crossing of the cold front over Cape Town is obscure but must have occurred at about noon on November 15th. A slight resurgence of Range-action is evident some 6 hours after this, Fig. 14 (a).

The advance of the next depression K in (p) and (q) of Fig. 74 seems to lead to the birth of a secondary K' with the occlusion of K. The crossings of the cold fronts of both K and K' have been indicated in Fig. 14 (~~a~~z), but they are very indefinite and were probably too far south to be rated crossings at all. The considerable Range-action of November 18th once again seems to bear no clear-cut relation to the cold-fronts.

As shown in Fig. 74 (s) and (t), the next large depression L also appears to pass clear of Cape Town, to the south, in spite of which a resurgence of Range on a minor scale was evident at Cape Town.

Example 2^o.

In Fig. 14 (a) it will be noticed that the next large bout of Range action occurred on December 3rd, 1944. The synoptic charts for the immediate advance period from December 1st are reproduced in Fig. 75 (a) to (e). As before we can trace the progress of depression A and its follower B to the stage where at (c) A seems to have given birth to a secondary A' and B to have exhausted itself under the influence of a prominent anticyclone. The cold front of A or of A' would have crossed Cape Town at about noon on December 2nd, in good agreement with the backing of the wind from north-west to south, but this time is 12 hours ahead of the development of Range-action as shown in Fig. 14 (a).

With agreement in some cases and non-agreement in others we are obliged to form the tentative conclusion that the mere passing of the cold front of a depression over Cape Town cannot in itself explain the ascendency of Range-action. On the other hand, we cannot but be impressed by the significance of the sudden disappearance and dissipation of certain depressions, just at the time that Range-action becomes prominent at Cape Town. In Fig. 14 (a), for instance, it will be noted that the powerful surges of November 6, 8, 13 and 18th, 1944, correspond with the apparent exhaustion of depressions B, E, G and K respectively, and similarly on December 3rd, 1944, the prominence of the Range seems to bear some relation to the vanishing of depression B of Fig. 75 (b). The accuracy of the synoptic charts, of course, is here called into question, but when the author raised this point with the Admiralty meteorologists, he was given the assurance that

> "The positions and movement of the depressions in most cases can be regarded as being accurate, having been determined by a number of factors which are known when the charts are analysed. The distortion of the chart in no way affects their position."

61. Recorded Features of Cold Fronts.

From the rather general purview in the last section, we proceed to a more exacting scrutiny of possible relationships in the light of the meteorological records obtained at the Range Laboratory at Cape Town.

Example 3^{o}.

The winter occurrence of Range of June 20th, 1945, Fig. 14 (b), is selected for the next example as being one for which synoptic charts are available in addition to the more local data.

The synoptic charts (a) to (l) of Fig. 76 show the depressions in existence over the period June 15th to 24th, 1945, and their identification and the passage of the fronts are indicated, as before, upon the weather-tide chart of Fig. 14 (b).

Depression A would seem to have advanced until at stage (d) it became so unstable as to break up into secondaries. The crossing of the cold front at about 22 hours on June 17th gave rise to no disturbance.

Depressions B and C, meanwhile, coming up behind formed a peculiar liaison as shown in Figs. 76 (e) and (f). After very rapid progress in the early stages, B became almost stationary at (g), while C mysteriously disappeared just at the time that Range action at Cape Town grew to large proportions on June 20-21st (Fig. 14 (b)).

Reverting to charts (f) and (g), Fig. 76, two cold fronts associated with depressions B and C would appear to have crossed over Cape Town, the first only a few hours before the time (02.30 hours, June 20th) of chart (f), and the second some time during June 21st. The passage of these cold fronts may be identified in Fig. 77, which synchronises the records of the barograph, microbarograph, thermograph and anemometer and superimposes them upon the original marigram for June 19th and 20th, 1945. The original anemogram for this period is separately reproduced in Fig. 78, and the microbarograms for June 19, 21 and 23 have already been presented in facsimile in Figs. 62, 63 and 64.

The rough indication of the synoptic chart, Fig. 76 (f), is confirmed by the greater detail of Figs. 77 and 78. From the anemogram, (Fig. 78), we see that at about 19.50 hours on June 19th, the wind which had been blowing gustily from N.N.W. at an average velocity of 20 mph, suddenly backed round to a somewhat steadier Westerly wind thereby marking the arrival of the cold front. At that time also, as the barogram and thermogram of Fig. 77 show, there was a sharp, if small, pressure rise and a simultaneous drop in temperature. The microbarogram of Fig. 62 (reproduced also in Fig. 77), shows very clearly the pressure rise and fluctuations defining this particular front.

The second cold-front of June 21st, 1945, suggested by the synoptic charts, is also clearly identifiable in a similar way in Figs. 63, 77 and 78, having crossed Cape Town at about 10.27 hours. A point of some interest in Fig. 78 is the apparently periodic fluctuation in wind-velocity as revealed by the mean lines superscribed on the anemogram. Similar quasi-periodic variations of pressure are detectable in the microbarograms of Figs. 62 and 63. The significance of these effects will not be questioned at this stage, but we shall nevertheless, in the next chapter, endeavour to explain them on the basis of the existence of air-waves.

The obvious general association between the disturbances generated in the harbour and the passing of these depressions is well portrayed in Fig. 77, which bears comparison with Fig. 14 (b). From conditions of utter calm, both of sea and atmosphere, on June 19th, 1945, we observe the sudden approach from over the open ocean of the travelling depression, B, of Fig. 76 (f). Barometrically, this depression was not a very pronounced one at Cape Town; yet it was marked by the advent of a very sudden rush of air from N.N.W. commencing at 11.15 hours on June 19th. During the ensuing 2 hours pressure dropped quite sharply and thereafter levelled out.

The sea disturbances, even after the arrival of this warm-sector air-mass, remained negligible until about 15 hours (some 4 hours later), when 17 min. oscillations (predominantly) were stimulated in Table Bay. With the crossing of the cold front 5 hours later again, at 19.50 hours, there was still no perceptible change in these long sea oscillations. Not until about 22.30 hours, or 2½ hours after the frontal crossing, is there evidence of shorter period disturbances penetrating the Duncan Dock and stimulating the transverse seiches. The local wind in all this time had blown with an average velocity of only 20 to 25 mph with peak gusts not much above 35 mph.

The oscillations in the Duncan Dock grew larger and larger with progress of time throughout the following morning of June 20th, and longitudinal seiches became conspicuous from about 09.30 hours on that day. Underlying these more rapid perturbations, the long period seiches (17 mins. or greater) persisted and grew, if anything, more obvious as depression F of Fig. 76 (k) moved in upon the scene.

The considerable barometric low of the second depression of June 21st, 1945, preceded by a N.N.W. wind of high intensity and long duration, reaching a peak at 04.30 hours, failed to produce as severe Range effects as its milder predecessor of June 19/20th. The sea disturbances from this second depression are seen to have been subsiding to a minimum at about 09 hours on June 22nd at the very time that the warm sector air mass of the third and succeeding depression was blowing in from the N.N.W.

Example 4°.

For our next example we take the very interesting case of July 7/8th, 1945, when a travelling depression of some violence passed in close proximity to Cape Town. The track of the depression centre in this instance was probably only a few hundred miles south of the Cape Peninsula, for at the height of the storm the barometer fell to the remarkably low level of 29.56 ins.

The wind which had blown gustily from the N.W. for several days, veered suddenly to the West with the advent of the depression trough. This concurrence of the cold front with the lowest pressure is consistent with the conditions near a cyclonic centre, and the remarkably sharp drop and equally sudden rise of pressure between 02 and 03 hours on July 7th, lend support to the contention that Cape Town received almost the full fury of the centre of the storm.

The general conditions are pictured in Fig. 14 (b), from which it will be seen that mean sea level at Cape Town was raised as much as 1'-3" above the normal average level (3 ft. above L.W.O.S.T.). The concurrence of high spring tides at the precise moment of crossing of the depression raised the overall sea level to 6'-6" above L.W.O.S.T., which in conjunction with the high seas and ground swells then running, led to an inundation and flooding of the Milnerton coast. Figs. 79 (a) to (d) show the havoc and destruction wrought upon that part of the shores of Table Bay.

For finer details of the meteorological and sea conditions prevailing at Cape Town, we refer to Figs. 65, 66, and 80. Fig. 80 carries the pressure, temperature and wind records superimposed upon the marigram for the period. The barogram of Fig. 80 shows the funnel like nature of the core of the depression and the numerous fluctuations that preceded and followed it, some of which are identifiable in the microbarogram and thermogram. Reference to Figs. 65 and 66 establish that these fluctuations correspond with repeated squalls which deluged Cape Town with blasts of wind and heavy intermittent rain.

The same general trend of disturbances in the Duncan Basin is noted in this case as in Example 3°. Long period oscillations of about 45 and 20 mins. periodicity precede the shorter period seiches, which only begin to be pronounced from about 22 hours onwards on July 5th, some 31 hours after the local wind had been blowing with moderate but increasing velocity from N.W. and W.N.W. But whereas in Example 3° the short-period commotion in the Duncan Basin followed after the crossing of the cold front, in this case it commenced long before the arrival of the equivalent front at 02.30 hours on July 7th (compare Figs. 77 and 80).

The embroidery of the marigram of Fig. 80 grows steadily larger throughout July 6th and 7th, and reaches its crescendo during the late hours of July 7th and the early morning of the 8th, after which it gradually diminishes in the 24 hours of calm that succeeded the storm. It is noticeable that during the building up of this embroidery in the 24 hours of July 7th, numerous pressure fluctuations, identified with squalls and having the characteristics of waves, crossed over Cape Town. Oscillations of the wind, detectable both in the velocity and direction records, appear to accord with some of these pressure waves.

Example 5°.

We take now another example of a depression of exceptional barometric intensity which crossed over Cape Town without producing Range effects such as might have been expected of it. The case was that of September 3rd, 1946, depicted in detail in the composite record of Fig. 81.

The depression was preceded by strong south-easterly winds prevalent throughout September 1st and notable for the periodicities reflected in both their velocity and direction. These winds would appear to have stimulated long-period seiches in Table Bay, which, with the tailing out of the wind and an increase of barometric fluctuation, reached fairly large amplitudes between 03 and 06 hours on September 2nd.

The arrival of the warm front of the depression is defined by the temperature drop (cf. p. 199) and the increase of wind velocity at about 08,30 hours on September 2nd, when wind direction also took a North-North-Westerly set. During the next 24 hours this wind blew with some fluctuation and gustiness at an average velocity between 10 and 20 mph, while pressure dropped sharply towards its trough at 06.30 hours on the 3rd. Shortly thereafter at 08 hours the wind backed suddenly with the arrival of the cold front. A secondary cold front appears to have followed close in the wake of the primary at 13.30 hours on September 3rd, when the wind veered round to the South again after a short return to its N.W. inclination.

The agitation in the Duncan Basin accompanying this depression takes once again the same general configuration as the disturbances of the previous examples, although the amplitudes in this case are generally much less. The short period oscillations are preceded by longer ones, which tend to show maximum amplitude just before the higher frequencies attain their greatest magnitude. It is to be noted that there was some diminution of the disturbance between 15 and 17 hours on

September 3rd before it increased again to maximum amplitude at about 20 hours on the same day. This may or may not have some connection with the apparent primary and secondary cold fronts, although these fronts are diffuse and not very obvious barometrically.

Example 6°.

This and the next example are given to show how Range can develop in circumstances of almost perfect local calm.

On the occasion of November 14/15th, 1945, the weather characteristics for Cape Town were as reflected in Fig. 15 (a) and in greater detail in Fig. 82. It will be seen that the local wind remained entirely negligible at the very time the agitation in the harbour reached peak proportions. The general wind-drift, nevertheless, was from the North-West on a falling barometer, and the Range disturbance in this case preceded the main trough of the depression and any diffuse cold front that may have accompanied it. It is to be noted that this incidence of Range was as severe in magnitude as that ushered in by the considerable storms of Example 3° (Fig. 77).

Example 7°.

Another such case of Range-action developing during fine, calm weather at Cape Town, was that of December 17th to 20th, 1946, for which the general conditions are shown in Fig. 83.

Unhappily the tide gauge developed a fault from bad electrical contacts throughout most of December 17/18th, and the marigram record for this period is missing so that the ascendency of the Range disturbances cannot be followed. By the time the fault was located and corrected, the oscillations had attained to maximum proportions, far larger, relatively, than anything shown in the previous examples notwithstanding the fact that local wind was negligible and the day calm and fine.

It was noticed on this occasion that well defined bands of light cloud, well separated by blue sky, but stretching across the whole dome of the firmament on a north-south front, were racing overhead from the North-West. To judge by the speed of progression of their shadows they must have been travelling at about 40 mph. Fig. 84 is a photograph of portion of the sky as enlarged from a frame of a 16 mm motion-picture taken at the time, showing the wave pattern in the clouds.

The author took cine-photographs of the very considerable surge action taking place in the 'cut' or entrance channel to the Alfred Basin (Fig. 4). Water was surging in and out here in a spate which must have attained velocities of 7 or 8 knots.

It is clearly not possible from Fig. 83 to identify any cold front with the remarkable embroidery of the marigram. The barogram, however, shows that two depression troughs passed over Cape Town, the first between 17 and 19 hours on December 17th, and the second some 24 hours later, on the 18th. Barometrically, however, these troughs were small and of easy gradient.

Other instances of this kind, in which Range-action developed under conditions of local calm, have been fairly numerous: a few other occasions have already been cited in Section 59, (p. 164).

The above examples may be regarded as typical of the varieties of form and mode of generation of Range-action of the shorter-period kind in Table Bay Harbour. Restrictions of space and time prevent presentation of more detail in this work.

While the accumulated evidence so far establishes incontestibly that Range-action at Cape Town is closely linked with the passage of travelling depressions of the South Atlantic, the particular manner in which the sea disturbances are generated by the depressions is not immediately evident from the facts thus far considered. That the cold fronts of these depressions are specifically responsible for the phenomenon is not proved, although it can be said that there are strong implications that air-waves or barometric fluctuations, preceding or following in the wake of these fronts, have important bearings on the issue; further, we have noted that the exhaustion or dissipation of the depressions seems also to be related thereto.

62. Hypotheses on the Meteorological Origins of Range.

The anomalies to which we drew attention in Section 59 (p. 164) remain still largely unresolved, although the connection between travelling depressions or barometric disturbances on the one hand and Range-action on the other can now be accepted as fact. Some of these anomalies have been further reflected in the examples of the last section, and their explanation at this stage demands a certain amount of conjecture.

If we recognize the possibility that Range (deriving from purely meteorological sources), may be born of several distinct causes associated with travelling depressions, each of which may operate independently or in unison with the others, we may venture at least two plausible hypotheses to account for the Range phenomenon and explain away the difficulties. These individual modes of generation may for the present be tersely postulated in the following:

a) Generation by Air Waves (Barometric and Anemometric).

Here it is believed that air waves are a common feature of barometric depressions and are frequently to be found along the marginal interface defining the cold front, itself an atmospheric wave. By means of fluctuating vertical pressure and wind traction of the surface of the sea, it is supposed that these air-waves generate sea-waves or swell with a wide range of periodicities, including visible surface-waves and invisible ground-swells. The long arm of the cold front of a depression, in terms of this concept, acts as a broom in sweeping sea-waves before and behind it.

b). Generation by the Exhaustion of Depressions.

A travelling depression of some intensity elevates the surface of the sea beneath it. As long as the depression moves forward slowly or varies intensity gradually, it is possible for the entrained body of water to conform with the rate of change by rising or dispersing, as required, in weak currents. It is possible, however, to visualize very sudden intensification, cessation of forward movement, or exhaustion, of a depression, caused by a recession or inrush of neighbouring anti-cyclones, such that the normal stability of the elevated water mass is upset. Long waves in such circumstances would almost inevitably develop in conjunction, no doubt, with shorter swells from increasing or dying winds, as the case might be; these would tend to radiate outwards from the depression centre.

CHAPTER IX

AIR-WAVES AND DISTURBANCES OF THE ATMOSPHERE

> 'As soon as a lighter fluid lies above a denser one with we
> defined boundary, then evidently the conditions exist at this bo
> ary for the origin and regular propagation of waves, such as we
> familiar with on the surface of water'.
>
> —Hermann von Helmholtz.
> Ueber Atmospharische Bewegungen, (1888)

63. The Suggestion of Waves in the Atmosphere.

We have already shown in Section 49 (pp. 144-145) that long-period seiches in Table Bay are infallibly linked with the incidence of prominent barometric oscillations of the atmosphere over Cape Town. We have further noted in the last chapter that on some occasions when Range-action has developed out of the storm conditions accompanying travelling depressions, there have been peculiar quasi-periodic fluctuations in the surface wind-velocities and in the barometric pressure. Chrystal had observed the same sort of thing over the Scottish lochs, and had concluded that barometric inequalities and wind-variations of apparently periodic character were the major cause in the stimulation of lake-seiches, (Section 31, p. 86). Chrystal, however, was cautious about attributing the pressure-fluctuations to the existence of air-waves, largely because strictly periodic variations were rarely encountered, but our own analysis of the oscillations of the atmosphere on those occasions already cited in Section 49, have suggested that the irregular nature of the barometric undulation may be accounted for in the co-existence of several atmospheric wave-trains of different periodicities, some of which appear to be higher harmonics of the main train.

The question now before us is whether, in fact, air-waves are a feature of atmospheric disturbances, and, if so, in what circumstances they are engendered, and how they can be held to account for the phenomena of coastal seiches and sea-vibrations.

64. The Overworld and Underworld.

We return to our consideration of the circulation of the earth's atmosphere (Section 55, p. 157) and the polar-front discontinuity, and shall introduce the conception of Sir Napier Shaw's "Overworld" and "Underworld"[*].

It was Helmholtz who first introduced the idea of the stratification of the atmosphere in his attempt to account for air circulation on sound hydrodynamical principles. He was led to the concept of the atmosphere existing in a series of ellipsoidal shells with the earth's pole as major axis, each shell containing a layer of air of uniform entropy, but different in entropy value from contiguous layers, (Fig. 85)[†]. Observations and entropy calculations have verified that the isentropic layers of the atmosphere do conform generally with this structure[§]. Sir Napier Shaw has distinguished the layers by an arbitrary boundary surface taken tangential to the earth at the equator. The atmosphere above this bounding surface he called the Overworld, and all layers below it, cutting the earth's surface at an angle, the Underworld, (Fig. 85)[‡]. Show identifies this demarcation between the Overworld and Underworld as being synonymous with the polar-front discontinuity[**].

It is largely the interplay in contiguous layers of the Overworld with the Underworld that is responsible for the polar-front phenomena of the travelling depressions. Shaw

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[*] Napier Shaw; (l.c. ante p. 39), [32], Vol. III, p. 316.

[†] 'Ueber atmospharische Bewegungem', 1888; cf. Shaw, (ibid.), [32], Vol. IV, pp. 58-61: see also Brunt, (l.c. ante p.112), [59].

[§] Shaw, (ibid.), [32], Vol. III, Fig. 95, p. 252.

[‡] Ibid., [32], Vol. III, p. 316; also Vol. IV, p. 60.

[**] Ibid., [32], Vol. IV, p. 317.

points out that the property of entropy creates in the atmosphere layers as individually separate as layers of liquid of different density[*]. These layers have a natural resilience which is only destroyed through the agency of water vapour, weather being, in effect, the result of this action.

Helmholtz, investigating the relative motions of two isentropic layers of air at their surface of separation, showed that on theoretical principles gravity waves must be set up, similar to the waves induced by wind on water. If the two air streams have equal and opposite velocities the waves take the form of stationary waves; normally, however, with unequal air-currents, crossing each other at an angle, they propagate at a velocity representing the difference between the component velocities of the air streams in a resolved common direction.

65. Travelling Depressions as Breaking Waves of the Atmosphere.

Helmholtz attributed the formation of cyclones to the general interaction of opposing air streams:

> 'On account of the numerous local disturbances of the great atmospheric currents, there will, as a rule, be formed no continuous line of separation, but this will be broken into separate pieces which must appear as cyclones.
>
> 'But as soon as the total mixed masses have found their equilibrium the surfaces of separation will again begin to form below, and new wave formations will initiate a repetition of the same processes'[†].

This idea was later taken up by V. Bjerknes in developing the polar-front theory which we have already referred to in detail in Section 56 (p. 159)[§].

It is now commonly accepted that surface cyclones are related to the roughly regular wave-pattern found in the isobars of the upper air charts, (which have become available

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[*] L.c. (ante p. 39), [32], Vol. III, p. 302.
[†] l.c. (ante p. 181), [32], Vol. IV, p. 63.
[§] Cf. Shaw, (ibid.), [32], Vol. III, p. 31.

only comparatively recently in the history of meteorology). This wave-system encircles the hemispherical upper air in latitudes just north (or south) of the high-pressure doldrum areas of the temperate zones, and has in general fewer cyclonic centres - sometimes as few as three - girdling the earth[*].

We shall here advance the suggestion that travelling depressions of the temperate zones are manifestations of the vortical breaking at the earth's surface of the huge atmospheric waves formed between different isentropic layers at the polar-front discontinuity. Fig. 85 shows that such a discontinuity would intersect the earth's surface along a circle of latitude, and waves at the interface, in their normal progression from west to east would be running over a variable depth of atmospheric ocean, the depth diminishing from high latitudes towards the equator. In consequence the atmospheric waves would be subject to the same general turbulence and retardation that accompany breaking sea-waves on shoaling ground, and would tend to form the vortices characteristic of the travelling depressions.

This behaviour of atmospheric waves was envisaged by Helmholtz:

> 'The boundary surfaces of different strata of air, along which the waves travel, have one edge at the earth's surface and there the strata become superficial. Experience also teaches, as does the theory, that water waves that run against a shallow shore break upon it, and even waves which originally run parallel to the shore propagate themselves more slowly in shallow water. Therefore waves which are originally rectilinear and run parallel to the banks will in consequence of the delay become curved, whereby the convexity of their arcs is turned towards the shore; in consequence of this they run upon the shore and break to pieces there. ....I therefore believe there is no reason to doubt that waves of air which in the ideal atmospheric circulation symmetrical to the [earth's] axis could only progress in a west-east direction, must, when once they are initiated in the real atmosphere, turn down towards the earth's surface and break up by running along this in a north-westerly direction' [in the northern hemisphere].[†]

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[*] Cf. Rossby: (l.c. ante p. 164), [86].
[†] L.c. (ante p. 181), [32], Vol. IV, p. 63.

Such a conception, applied to travelling depressions, would explain the arc-formation of the cold fronts and the fact that cyclonic storms follow each other in succession as related families and in approximately regular periods.

Reference to Figs. 14, 15 and 16 will show that the depression troughs in the barometric pressure curve are actually suggestive of wave-formation. If these distended weather-charts are condensed by contracting the time-scale, the wave-pattern becomes even more singularly obvious. Fig. 86 has been prepared in this way by plotting 5-day averages of mean temperature, pressure and sea-level over the years 1943 to 1946. The result is a very interesting series of curves showing the fluctuations of these properties over a number of years.

Besides the year by year changes which are apparent in these diagrams, there are the very obvious variations taking place over a number of days, which upon close scrutiny are found to be strongly suggestive of being cyclic. In fact, harmonic analysis* of the pressure and temperature curves identifies unmistakably in each a sequence of waves of periodicities 122, 72, 36, 24, 17½, 14½, 11½ days, running as a theme upon the periodic annual variations.

We are thus led to ask whether, having regard to the supposition that travelling depressions are indeed waves or oscillations of the atmosphere, it is rational to suppose that they would always exhibit the same combination of frequencies, or whether in fact the apparent cycles are only purely random. The author is aware of the controversial nature of this subject and of the conflicting views commonly held regarding the existence of periodicities in weather-

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* Performed by Chrystal's Method of Residuation, cf. Section 89, p. 255 post.

phenomena, but the question has been very ably and dispassionately discussed by Sir Napier Shaw, who points out that a degree of resilience in the structure of atmospheric circulation will almost certainly give rise to states of oscillation, either natural or forced, depending upon the exciting causes and the orographical features forming the boundary conditions.* We cannot do better than quote him on this subject:

> 'No meteorologist would be prepared to deny the reality of the existence of the periodic changes in the general circulation which are regularly related to the day or the year, and in like manner the changes in any other natural interval might on analysis disclose a periodic change of a certain magnitude, but there is nothing which finds such general and easy recognition as the alternation of day and night and of summer and winter'†.

If the periodicities we have uncovered do exist in reality there must be some physical explanation for their presence: although it is not within the scope of this work to delve too deeply into this interesting theme, we are strongly tempted to speculate on the significance of the prominent 24, and 17½ day periodicities exhibited by the depressions.

From Fig. 14(b) it will be seen that particular depression troughs can be identified both at Cape Town and Port Elizabeth in such an unmistakable way as to show that their average speed of progression eastwards along the intervening circle of latitude (33° 57'S.) is about 37½ mph. At this speed and latitude the waves would take about 23 days to circle the globe. If some allowance were made for higher wave-speeds in the deeper atmospheric ocean further south it might possibly be found that 17½ days is the time that would be required for a depression wave to circumnavigate the earth at the latitudinal interface between the overworld and underworld. This would not necessarily imply that such waves would propagate entirely round the world: it would however indicate the free period of oscillation of the atmosphere

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* L.c. (ante p. 39), [32], Vol. II, p. 305.
† Ibid., [32], Vol. II, p. 318.

along the polar-front discontinuity and the frequency at which waves would tend to be generated. The 24 day periodicity could possibly be some variation of this deriving from the orographical effects of the land masses, and the other periodicities found might be harmonics or overtones or related to meridional oscillations.

Whether there is anything in this speculation on the physical meaning of these periodicities must be left to other analysts who are better qualified to judge, but we may draw some degree of confirmation of this outlook from the 24, and 36 day periods detected in the weather of the northern hemisphere by Weichmann and others*.

The implications are, then, that the cycles of occurrence are real and that the wave-theory of frontal depressions is confirmed by these findings. Cyclonic storms then would seem to be the eddies formed by a train of breaking atmospheric waves of numerous periodicities, some of which are harmonically related. The amplitude and phase-relationship of the concurrent periodicities will determine the magnitude of any storm and explain why some are of exceptional violence and others comparatively innocuous.

The regularity of the 36, 24, 17½, 14½ and 11½ day periodicities over so many years (Fig. 86) would seem to commend itself to the attention of meteorologists as a valuable tool in weather forecasting, especially in the South African coastal regions. No doubt similar trends could be discovered over the great land-masses and long-range forecasting of weather thereby greatly assisted.

From a more exact knowledge of the amplitudes, periods and phases of the harmonic components than the author has had time or opportunity to evolve in these pages, it should be possible to compound future weather trends by working from the data

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* L.c. (ante p. 39), [32], Vol. III, p. 32.

of the immediate past. Reasonably accurate forecasts up to periods of 17 days ahead of current time should be possible on this basis[*]. Such forecasting would also be of value from the point of view of anticipating well in advance really severe Range-disturbances at Cape Town.

In Section 10 (p. 58) we referred to a slow fluctuation of mean sea-level, conforming with barometric pressure. This is obvious in all the diagrams of Figs. 14 to 16, and in the light of what has been said above, it can be regarded as consisting of a series of small amplitude, very long period, forced sea-waves, accompanying the barometric disturbances. The relationship is further demonstrated in Fig. 86. Unfortunately, owing to numerous failures of the recording tide gauges and the possibility of incorrect readjustments, it cannot be said for certain that mean sea-level actually underwent the overall falling trend reflected in Fig. 86; nevertheless, it will be seen that the same long-period fluctuations as occur in the pressure curves are evidenced inversely in the mean sea-levels.

Although we have only drawn attention to the most obvious periodicities in each annual record of Fig. 86, it is apparent that other long-term secular changes are at work producing variations of pressure and temperature from year to year.

In Section 14 (p. 43) we advanced an explanation for this by ascribing it to slow mutations of the hemispherical high-pressure belts, probably of a cyclic nature. Such a slow perturbation of the polar-front discontinuity could account for the lessening of the severity of Range-action that

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[*] Applications of this kind to the forecasting of river flow have been made with some success apparently by engineers in the U.S.A. Cf. Person, 'Cyclic Variations in Columbia River Flow Studied', Civil Engg., 1950, [87], p. 267.

has been noticeable over the years since 1940/41.

66. Smaller Atmospheric Waves accompanying Depressions.

Helmholtz in his investigations of atmospheric circulation proved the existence of more than one form of wave. To quote him:*

> 'The calculations performed by me show further that for the observed velocities of the wind there may be formed in the atmosphere not only small waves, but also those whose wave-lengths are many kilometres, which when they approach the earth's surface to within an altitude of one or several kilometres, set the lower strata of air into violent motion and must bring about the so-called gusty weather, the peculiarity of such weather (as I look at it) consists in this, that gusts of wind often accompanied by rain are repeated at the same place, many times a day, at nearly equal intervals and nearly uniform order of succession.'

More recent students of dynamic meteorology have identified the existence, on theoretical grounds, of several types of waves that may occur at the frontal surfaces of cyclonic depressions. Briefly they may be classified† as:

(a) Short unstable waves, giving rise to billow clouds, of a wave-length of a few kilometres and a period of some minutes.

(b) Short stable waves of wave-lengths from a few kilometres up to about 500 kms.

(c) Unstable cyclone waves of wave-lengths from 500 to 3000 kms.

(d) Long stable waves of wave-lengths greater than 3000 kms.

The last Section can be said to have dealt with waves of type (c) and (d), but the types with which we are now more particularly concerned are those falling under the classification of (a) and (b).

It would seem to be obvious from our consideration of the structure of a travelling depression (Fig. 72) and

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* L.c. (ante p. 181), [32], Vol. IV, p. 62.

† Cf. Petterson, 'Weather Analysis and Forecasting', (New York), 1940, [88], pp. 309-319.

the Helmholtzian concept of the genesis of air-waves that such waves must form along the frontal surfaces between the warm-sector air-mass and the intruding cold air. According to Pettersen the warm-sector air will perform an oscillatory motion both horizontally and vertically on this account.

If such waves exist we should expect to find evidence of them in observable fluctuations of the barometer and anemometer. Several cases of this kind have already come to our notice while identifying features of the travelling depressions in the last chapter (cf. pp. 171, 174, 178), but we shall here draw upon other evidence in the literature to demonstrate the existence of these waves.

Chrystal[*], as we have seen, recorded many examples of what he called 'quasi-periodic' fluctuations of barometric pressure, and Fig. 24 is typical of his observations. Here the microbarograms are observed to have an obvious wave-pattern, confused, however, by numerous small irruptions, all of which could possibly be the result of interference of trains of waves of differing amplitude and wave-length. Such pressure fluctuations as these, amounting to about 0.1 to 0.3 mm and of 5 to 10 minutes period, have been noted as being common during spells of cold weather[†]. Shaw has pointed out that such embroidery of the barogram tends to its irregular form during the advent of squalls and thunderstorms, but it is also capable of a very regular form which has "no apparent relation to weather". Scattered throughout Shaw's extensive four volume 'Manual of Meteorology' are numerous examples of

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[*] L.c. (ante p. 86), [42].

[†] Cf. Humphreys, 'Physics of the Air', (New York), 1940, [89], p. 239.

barograms and anemograms reflecting very obvious oscillations of very pure form with periodicities of the order of 10, 20, 40 and 60 minutes*. Further, according to Shaw:

> 'The striped appearance of cloud in the sky may also be an indication of wave-motion marked by condensation in the ridges.'

but of this there seems hardly much doubt, for Brillouin† has pointed out that the upward motion of air, which gives rise to cloud formation, takes place in the boundary between two layers of different entropy where Helmholtz has shown waves tend to develop. The cases of observed lenticular, corrugated or tessellated formation in clouds are so legion that it must be presumed that wave-formation is actually a very common occurrence in the atmosphere, just as it is in the sea.

67. Line-Squalls as Atmospheric Bores.

Returning then to our concept of wave-formations occurring at the actual boundary-surface of the cold-front of a travelling depression, we may seek to show that they will explain not only the line-squalls and gusty weather that accompany the front, but also some of the cloud-formations that are characteristic of it (cf. p. 162).

We may cite the occasion of July 7/8th, 1945 (Example 4° of Section 61, p. 173) for evidence of waves running down the surface of the cold front. As we have seen, the arrival of the cold front at Cape Town, (that is, at its intersection with the earth), is clearly established as having occurred at about 02.35 hours on July 7th, when the centre of the depression was probably within the near vicinity. From then on a continuous embroidery on the

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* L.c. (ante p. 39), [32], Vol. II, p. 376; Vol. III, pp. 28-30; Vol. IV, pp. 31, 145, 160, 276.
† 'Vents contigus et nuages', ibid, [32], Vol. IV, p. 62.

barogram, as the anti-cyclone moved in behind the depression, defined the squalls following in the wake of the cold front. Figs. 65 and 66 show the pressure surges that accompanied identified squalls, when sudden wind-gusts and heavy rain broke over Cape Town.

These pressure-surges are perhaps not very suggestive of sinusoidal waves. They conform more to the analogy of estuarine bores resulting from the piling up of tidal water at constriction points and shallows of river-mouths, or of breaking waves and waves of translation as envisaged by Scott Russell (p. 105). Cornish has given us detailed accounts of tidal bores, a common feature of which appears to be the smaller parasitic waves that ride, so to speak, on the back of the parent-bore, just behind the advancing wall of water*. Close examination of Figs. 65 and 66 suggests the same sort of thing in the equivalent atmospheric bores, which, in effect, line-squalls and, indeed, the larger cold fronts of the depressions themselves appear to be. The microbarograms of Figs. 62, 63 and 64 show the cold fronts to have the same characteristics, and these, after all, are the barometric features we should expect of the supposition of Section 65 (p. 183) that travelling depressions are atmospheric waves breaking on shoaling ground in the atmospheric ocean.

Cornish made the interesting observation that squalls of a duration of about 4 minutes pass through a storm at speeds about 10 mph above the average speed of progression of the storm†. This conforms with the concept that squalls are a manifestation of breaking air-waves advancing in the diminishing depths of an atmospheric sea, whose free surface is the inclined cold-front. Just as presaged by Helmholtz (p. 188) the waves which tend to form at the

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* L.c. (ante p. 113), [60], Chapter on Bores.
† L.c. (ante p. 113), [60]

cold-front surface between the different isentropic warm-section and cold-air-mass layers, run down the cold-front and assume the character of breaking waves or bores which expend themselves in violent gusts of wind and rain on striking the earth's surface. Shaw[*], without attempting to explain line-squalls positively on this basis, nevertheless envisaged this possibility by repeatedly drawing attention to the

> '....analogy between the phenomena of a train of breaking waves on a shelving shore and the recurrent showers introduced by a line-squall, that are often found in the south-west quadrant of a cyclonic depression during the transition from south-west winds to north-west'. [Northern hemisphere].

The cloud-formations peculiar to the cold-front (Fig. 72) may perhaps be partly explained as a reflection of wave-energy at the intersection of the cold-front with the earth's surface, for here there would tend to be an updraught of nimbus cloud, and the lenticular alto-cumulus clouds that precede the cloud-castles could well indicate the atmospheric ripples born out of this turbulence.

68. Periodicity in Wind-Gustiness.

In the last Section wind-gustiness was mentioned as a definite accompaniment of squall-waves in the atmosphere. If waves are actually a physical reality in the atmosphere, then it must clearly follow that the velocity of air-streams giving rise to such waves will be influenced locally by the oscillatory motion of the air-particles. To take an example, let it be supposed that a surface air-current, on the move at say 40 mph, gives rise to billows in the atmosphere, whose existence necessitates an oscillatory movement at the earth's surface of 10 mph (maximum), purely on their own account. The recorded wind-effect at

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[*] L.c. (ante p. 39, [32], Vol. II, pp. 27, 380; Vol. IV, pp. 63, 286.

ground-level would then be a fluctuation between 30 and 50 mph at regular intervals, producing an impression of gustiness.

It is true that surface irregularities and the turbulence that go with them must introduce a large degree of disorder and randomness in wind-recordings at or near the earth's surface, but, for all that, we find that the underlying wave-form is often very clearly and undeniably portrayed. This is exhibited in the anemometer records taken by Dines at an elevation of 98 feet above ground level on Pyrton Hill in Britain*. The normal ribbon of wind-velocity in the anemograms showed the familiar irregularities from wind-gustiness, but a more open time-scale that was tried out showed that this irregularity carried a strong suggestion of wave-form. Dines tethered a small balloon by a thread 100 feet long to the top of the anemometer pole on Pyrton Hill, and recorded the variations in its altitude, and, here again, the embroidery of the record is very suggestive of wave-pattern. Besides the frequent alternations of wind-direction that take only a few seconds, Dines found quasi-periodic fluctuations spread over several minutes. Apart from this fairly high frequency variation in wind-velocity, there is often evidence of longer-period oscillations whose reality is undeniable as Shaw has pointed out†.

But in evidence of wave-form in wind-recordings we need go no further than our own measurements at Cape Town, which, as noted in Section 45 (p. 130), were obtained from an anemometer placed on the top of the grain-elevator at an approximate elevation of 150 ft. above sea-level. This anemometer, while perhaps not immune to small eddy effects from the tall building on which it was

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* Cf. Shaw, (l.c. ante p. 39), [32], Vol. IV, pp. 145-149.
† Ibid, [32], Vol. III, p. 29; Vol. IV, p. 31.

erected, had uninterrupted exposure to winds from the north-west, north and north-east directions, advancing direct from the sea or the Cape Flats. In the southerly directions orographical effects from Table Mountain and the nearby Signal Hill, however, would be a factor tending to deprive the recordings of some generality.

We may consider first the anemogram for June 19/20th, 1945, reproduced in Fig. 78. As we have seen from Example 3° of Section 61 (p. 171), the wind on this occasion rose suddenly from the north-west as the frontal depression moved in over Cape Town. It represented a definite mass-movement of air, the spearhead of which was travelling at a velocity of between 10 and 20 mph. The anemogram shows the familiar gustiness, but lying almost concealed in the dense ribbon of wind-velocity, there is an unmistakable pattern with wave-characteristics. Periodicities approximating 11 and 21 minutes, (one probably the second harmonic of the other), are identifiable in the first 5 hours of the passage of this air-stream over Cape Town. Extreme gustiness for the next 4 hours, however, occludes any underlying harmony.

With the arrival of the cold-front at 19.50 hours, marked by the veering of the wind, there is a noticeable reduction in high-frequency gustiness and a corresponding revelation of the low-frequency variation with apparent periodicities of 33, 16.5 and 6.7 minutes. A little later between 22 and 23 hours there is a remarkably regular fluctuation of wind-velocity approximating 6 minutes. Gustiness obscures the trace for the next several hours until about 05.30 hours on June 20th, when there is a recurrence of the 33 minute oscillation and its fifth harmonic, 6.7 mins.

A significant feature of these variations of wind-velocity is that they are often accompanied by corresponding cyclic changes in direction as may readily be seen in the anemogram reproduction in Fig. 77.

In all the anemogram re-traces of Figs. 80 to 83 we find the same story, oft repeated - namely, unmistakable periodicity in wind-velocity or direction on most occasions where high-frequency gustiness does not wholly obscure the issue.

With the crossing of the cold-fronts and line-squalls of Figs. 77 and 80, in particular, we find the overall fluctuations of wind-velocity and direction to correspond exactly with the barometric pressure-surges. This is very clearly defined at 19.50 and 24.00 hours on June 19th, and between 07 and 11 hours on June 21st, 1945, (Fig. 77), as also at 02.30 hours and throughout most of the day on July 7th, 1945, (Fig. 80).

From all this evidence there can be but one conclusion: that the supposed randomness in wind-gustiness may often be more apparent than real, and that gustiness is sometimes largely dictated by the orbital oscillations of the air in conformity with the passage overhead of atmospheric waves.

69. Co-existence of Wind and Barometric Oscillations.

It is noticeable from Fig. 77 and Figs. 80 to 83 that the wind in general appears to be a far more sensitive index of the presence of atmospheric waves than the ordinary barometer. This observation is explained by Helmholtz's theoretical prognostication[*]:

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[*] L.c. (ante p. 181), [32], Vol. IV, p. 65.

> 'When it is calm at the earth's surface the wind beneath the trough of the aerial billow is opposed to the direction of propagation, but under the summit of the billow it has the same direction as that [propagation]. Since the amplitudes at the earth's surface are diminished in the proportion $e^{-nh}/1$ with respect to the amplitudes at the upper surface, therefore these latter variations can only make themselves felt below when the depth is notably smaller than the wave-length. Variations of barometric pressure are only to be expected when decided changes in the wind are noticed during the transit of the wave'.

But the surface-wind, sweeping in from an open ocean, we may assume, obeys not only the wave-form motions of billows at the surface of separation of different isentropic layers of the upper air, but also the oscillations of surface air-waves as the result of the play of wind over water. For it is entirely rational to suppose that if a wind-stream, exerting traction on the surface of the sea, can generate water-waves in that fluid medium, then corresponding waves must, ipso facto, be set up in the atmospheric medium immediately overhead. Some of the wind-oscillations recorded in the anemograms may therefore be evidence of surface air-waves which would not always be accompanied by perceptible changes in pressure. Thus, in Fig. 77, very obvious wind-oscillations of a period approximating 5.8 mins. are to be found in the record of velocity between 14 and 15.30 hours on June 20th, 1945, when the wind was blowing from the west, although the microbarogram for that period (not reproduced here) showed no equivalent fluctuation.

The presence of minute barometric fluctuations on some occasions and not on others is a feature of considerable interest. On June 23rd, 1945, for instance, the microbarogram (Fig. 64) showed that decided pressure-fluctuations were accompanying wind-gusts from a generally south-south-east direction, although in the more violent winds of June 20/21st (Fig. 77), from the north-west, no such pressure-disturbances chequered the microbarogram trace, (Fig. 63).

It must be said that apart from the few barometric fluctuations found over-riding the cold-fronts and squalls from the north-west direction, the only really prominent high-frequency inequalities recorded on the microbarograms have been a feature of winds from the south-east direction. During really violent south-east gales, of which Fig. 69 is typical, the microbarogram shows a more frequent scalloping than that of Fig. 63. Although periodicity in such records seems non-existent, close scrutiny reveals that it is nevertheless there, as may be seen from the obvious pressure waves showing up quite clearly just after 2.14 p.m. in Fig. 69.

Just why south-east winds should be more subject to this pressure fluctuation than winds from the north-west is uncertain. It may have an explanation in Helmholtz's observation that pressure-disturbances from air-waves will only be felt at the earth's surface when the height above ground-level of the wave surface-of-discontinuity is shallow compared with the wave length of the waves. It may also be connected with the position of the observing station in relation to the surrounding orographical features, Table Mountain lying directly athwart of the line of approach of the south-east winds.

Where mountain-peaks obstruct the passage of strong air-currents, standing waves tend to be set up on the leeward sides in the same way that standing waves are created on the down-stream side of stones or boulders in moving currents of water. Lenticular formations of cloud are sometimes observed in this way near the summits of mountain-peaks, notably Mt. Pico in the Azores and

Mt. Etna in Sicily[*]. On rare occasions similar cloud-formations have been observed in the lee of Lion's Head at Cape Town, when the wind has had a south-westerly set, but for the most part the 'table cloth' of Table Mountain does not exhibit this structure. Nevertheless there seems to be other evidence to suggest that standing waves may often be there.

Thus in Fig. 87(a) we notice that pronounced long-period barometric oscillations occurred over Cape Town on September 12/13th, 1945, and again on the 16/17th. The wind-records for the same periods, Figs. 87(b) and (c), show concurrent wind-oscillations in strong air-streams coming from the south-east. The periodicities, which are very evident in the anemograms, are about the same in each case: namely, about 34 to 35 minutes, while those apparent in the barogram appear to be of the order of 38 minutes. Obviously these are one and the same and the discrepancy merely arises from the inaccuracy of estimating wave-lengths on the less open barometric time-scale.

These obvious air-waves represent in both cases the tailend of a mass of air moving over Table Mountain and Cape Town from a south-east direction. What, we are led to ask, is the significance of this oscillation that affects so powerfully both wind and barometric pressure? What also is the significance of the 34 minute periodicity, which has been detected on so many other occasions (cf. Section 68, p. 194), even when the wind blows in from the west (Figs. 77 and 81)? Why, moreover, do such oscillations tend to occur with sudden changes of average wind-speed?

Without the means, at this time, of being able to

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[*] Cf. Shaw, (l.c. ante p. 39), [32], Vol. III, p. 30.

verify a conjecture, the author is nevertheless inclined to think that these air oscillations are to some extent bound up with the oscillating basin formed by the amphitheatre of Table Mountain and its adjoining peaks. It is conceivable that standing air-waves are in evidence on the leeward side of this range whenever the winds blow steadily across it. As standing waves, they would not produce any variation of barometric pressure or wind-velocity at an observing station in the shelter of the mountains, until such time as the overall speed of translation of the air-mass suffered a change. In the event of the sudden diminution of wind-speed following upon the tailing out of the wind, the standing waves could be expected to become waves of propagation and then to register barometrically and anemometrically at the observing station.

The above surmise does not seem unreasonable and may possibly also account for the prominence of some of the long-period oscillation observable in the wind records, even when the winds are bearing from north-north-west. From that quarter the surface wind would run into the vertical barrier of Table Mountain and there tend to reflect, creating aerial seiches in much the same way as oceanic seiches develop in Table Bay. The phenomenon in the air may, indeed, be a close parallel to that occurring in the sea. This concept does not necessarily imply that the air-waves derive entirely from the frustration of an air-stream at the mountain-barrier, but rather that particular periodicities of air-waves become enhanced in amplitude of oscillation as a result of resonance in the bowl-shaped amphitheatre of Table Mountain.

In how far all this may help to account for the high-frequency microbarographic fluctuations found to exist during the play of southerly winds cannot be said. Similar small 'vibrations' of the atmosphere have recently attracted the attention of observers in the United States and are now being studied by the Rev. J. B. Macelwane[*] at St. Louis University, and their elucidation must presumably be awaited from that quarter. While these microbarographic vibrations seem to be commonly associated with strong winds, to the extent that Chrystal referred to them as a 'wind-blurring of the microbarogram'[†], it is not impossible that they may on occasion originate from other sources. Thus certain oscillations of pressure recorded on June 30th, 1908, by microbarographs in England were eventually correlated with the fall of a large meteorite in northern Siberia[§].

70. Long-Period Barometric Oscillations.

In Sections 51 and 52 (pp. 148-151) we noted that Range-action often assumed a 'dual-personality', insofar as really prominent long-period seiches rarely occurred concurrently with short-period agitation, and vice versa. It was noted too that years when short-period Range tended to be subdued were years when long-period Range seemed more frequently active, and vice versa. Such opposite characteristics suggest that the meteorological conditions giving birth to the phenomena may be fundamentally different and even assynchronous. The general meteorological conditions under which short-period Range-action develops, and their positive association with travelling depressions, have been elaborated in much of what has been dealt with up to now, but whether in actual fact they can be dissociated from the conditions

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[*] Cf. Time, Sept. 8, 1947, [90].
[†] L.c. (ante p. 86), [42].
[§] Cf. Shaw, (l.c. ante p. 39), [32], Vol. II, p. 377; Vol.III,p.30.

producing long-period seiches remains to be seen.

We have remarked already from the five examples of ordinary Range-action considered in Section 61 and Figs. 77 and 80 to 83, that there is generally an under-current of long-period sea-oscillations present throughout most of the time that short-period agitation builds up and dies out in the harbour basins: furthermore, that there is a tendency for such long oscillations to attain maximum amplitude before the shorter ones reach their peak magnitudes. All this is consistent with the advance of a long train of sea-waves from the open ocean, the longer ones of which outstrip the shorter, as in the ripple-rings that emanate from a focal point of disturbance on the surface of a smooth pond.

There remains then to examine in detail the circumstances in which very powerful long-period seiches can be generated without the accompaniment of the shorter-period vibrations of the sea. Three examples will be considered to permit of some identification of the features of local weather accompanying the disturbances.

Example 8°

The occasion of September 24-27th, 1945, is one of great interest. The general conditions prevailing at Cape Town are to be found in Fig. 14(b) and in greater detail in the composite chart of Fig. 88.

It will be seen that the disturbances in the Duncan Basin on this occasion(throughout September 24th) were entirely devoid of any high-frequency oscillations, notwithstanding that a depression trough of the usual type had just passed over Cape Town to the accompaniment of light winds from the north-west. The circumstances, in fact, might be no different from those of Example 4° or 5°, except that very pronounced barometric oscillations are here to be found on the rising pressure gradient. In all these cases (4°, 5° and 8°) the local weather was fine and calm and the wind-drift northwesterly, yet on this latter occasion, unlike the others, high-frequency effects were conspicuously absent.

The obvious association between the barometric fluctuations of September 24th and the long-period seiches set up in Table Bay is very evident from Fig. 88 (cf. also Fig. 67); but the later and almost equally prominent barometric oscillations of September 27th, it will be noted, failed to induce any equivalent sea-oscillation, presumably owing to the fact that the over-riding air-mass had by then veered to the south-east.

The seiches of September 24th caused strong surges of water through the harbour entrances, and the S.S. 'Samnegros', while entering the Duncan Dock at 18.30 hours, felt the brunt of this action by being deflected by the currents first to port and then to starboard.

Example 9°

The next example is that of September 30th, 1945, only a few days after the period just described. Here again (Fig. 89), pronounced barometric oscillations of relatively pure form, occurring in an overlying air-mass, that was drifting over Cape Town from the north-west at negligible surface velocity, are quite obviously responsible for the large seiches imposed on the waters of Table Bay.

During this spell, at 17.50 hours on September 30th, the S.S. 'Red Jacket' was observed by the author to be held in the grip of the current in the entrance of the Victoria Basin, while coming in to dock. For quite some time the ship was unmanagable even with the assistance of tugs.

Example 10°

One further example must suffice to demonstrate the consistency of the mode of excitation of long-period seiches in Table Bay in the absence of swell and high-frequency agitation.

On March 28th, 1946, (Fig. 90), on the rising pressure gradient of an anti-cyclone moving over Cape Town from the north-west with negligible surface velocity, powerful barometric oscillations are seen again to have been responsible for the extraordinary oscillations that were generated in the Duncan Dock.

The apparent periodicities of the atmospheric waves are found on approximate analysis to be of the order of 130, 82, 66, 36 and 15 minutes, values which tally closely with those in previous examples and the earlier cases cited in Section 49 (p. 145).

From Examples 8°, 9° and 10° we may recognise what appears to be a fundamental difference between long-period barometric oscillations invading the scene of Table Bay from the north-west and from the south-east. Those from the north-west usually are associated with insignificant surface-winds, whereas those from the opposite quarter (cf. p. 198 and Figs. 87) are invariably the tail-end waves accompanying a powerful surface-current of air. The atmospheric waves moving over Cape Town from the north-west have the best directional approach for exciting seiches in the bay, since their approach from the open ocean ensures a following train of long sea-waves. This will be apparent from Figs. 88 to 90, where the persistence of the seiches after the passing of the barometric disturbances must derive from in-coming sea-waves following in the wake of the air-waves. On the other hand, atmospheric waves advancing from the south-east supply only superficial energy to the sea from the landward side, and seem incapable of sustaining any large seiches in the presence of the frictional damping of the strong surface-winds.

Here we must note from Fig. 81, (as already recorded on p. 175), that seiches were in evidence during a fluctuating south-east wind on September 1st, 1946. These, however, reached large proportions only when the wind had virtually died out and strong barometric oscillations developed, as a result, we presume, of the turbulence created by the warm-sector air-mass moving in from the north-west and destroying the momentum of the south-east surface stream.

This latter instance affords perhaps a clue to the possible explanation of the phenomenon of large barometric oscillations, giving rise to coastal seiches. Can it be that they are the result of separate air-currents overrunning each other in the same way that faster waves on a sea coast may be observed to override slower ones in the face of a backwash? In this analogy one finds that the overtaking wave plunges and oscillates many times before it asserts itself again in progressive forward motion. Would not the vast atmospheric breaking waves, which we identify in the travelling depressions, perform similar turbulent oscillation in the event of one's overtaking another? We shall endeavour to answer these questions, partially at least, by referring to two occasions for which we have synoptic charts, when the phenomenon prevailed.

We return to the case of October 1st, 1944, referred to in Section 49 (p. 145) and featured in Figs. 48 and 57. Figs. 91(a) to (d) give the synoptic charts for the South Atlantic for the enveloping period, and we see from (a) and (b) that on September 29th and 30th, 1944, depressions C and D were advancing on a wide front across the southern ocean. At stage (c), 02.30 hours on October 1st, depression D has virtually over-taken C, and at (d) had merged with it. If these isobars are anywhere near correct, this can only mean that the larger and faster breaking wave overtook the smaller one, and they coalesced, presumably, in a tumble of atmospheric commotion.

The second case is that of April 8/9th, 1945, described already in Section 49 (p. 145) and pictured in Fig. 58. The synoptic charts for this occasion are presented in Figs. 92(a) to (d). Here we find a stationary low-pressure centre B, over the west coast of South Africa, being invaded by an occluding depression A, just at the time that the atmospheric oscillations and sea disturbances developed at Cape Town. At stage (c), just after the first barometric oscillations commenced, depression A is seen to have broken up into two by giving birth to a secondary depression A'. Here again we derive support for the belief that the sea and air oscillations are the direct repercussion of the galloping effect of one major depression-wave overtaking another.

Whatever the true cause of the barometric oscillations, it must be supposed that they occur as a result of the general resilience of isentropic layers and the intrusion of air into regions for which it is intrinsically too heavy.

There remains to accommodate the observations made at the beginning of this section. It is, however, very difficult to understand, with the limited amount of factual data before us, why sea-swell is not in evidence when this collision of air-masses takes place, or why there should be any greater tendency towards this commotion when the tracks of travelling depressions are presumably farther south and ordinary Range-effects are less frequent: the author must therefore leave this problem for others to unravel, but suggests that the movements of anti-cyclones are worthy of study in this connection.

71. The Reality of Air-Waves.

In this chapter we have attempted to show that air-waves are as much a common feature of the atmosphere as sea-waves are of the oceans. They arise largely as the result of the interplay of isentropically-resilient layers of air moving across each other at unequal velocities, often from different directions. Entropy is the property which gives to the layers a degree of elasticity permitting of oscillation, and water-vapour is the agent with which this resilience is ultimately destroyed.

The isentropic layers of the atmosphere envelop the world in ellipsoïdal shells, co-axial with the polar axis, but the main interplay of atmospheric circulation occurs at the particular shell surface which is approximately tangential to the earth at the equator, commonly known as the polar-front discontinuity. Waves of oscillation are set up at this interface in both hemispheres, the wave-fronts tending to lie north-south, and their direction of propagation being eastwards.

As a result of the diminishing depth of atmospheric ocean in decreasing latitudes, the waves of oscillation are retarded in the shallows and swung towards the equator, breaking, in much the same way as sea-waves on shoaling ground, in the temperate regions. These breaking waves or travelling depressions are vortical in character and follow each other in trains with an underlying regularity apparently dictated by the natural periods of oscillation of air in the hemispherical belts of the temperate zones: in the southern hemisphere, south of the high-pressure doldrums.

This pattern of behaviour is repeated on a smaller scale in the depression-waves themselves, and smaller parasitic waves override the parent depression and give rise to the familiar line-squalls and cloud formations, which are the usual accompaniment of such centres of weather. The ascent of moisture-laden air into the ridges of oscillating surfaces of discontinuity and its condensation there, gives rise to the wave-pattern often seen in cloud formations.

Air waves are indicated in meteorological recordings by the periodic nature of barometric pressure-fluctuation and wind-gustiness, which often confirm each other in showing the reality of the atmospheric oscillation. Sometimes, however, barometric oscillation is unaccompanied by any (surface) wind, and wind-oscillation may be without any corresponding pressure changes; these conditions are possible according to the height of the surface of discontinuity and the wave-length of the waves within it.

Besides the short-period air-waves which show up in microbarogram and anemogram recordings at Cape Town, with periods of only a few minutes, there are longer waves whose periods often show a consistency suggestive of an influence from local orographical features. It is thought that the semi-ellipsoidal bowl of Table Mountain and its companion peaks provides an oscillating basin wherein air-waves may form atmospheric seiches in much the same way that sea-waves form seiches in the waters of Table Bay.

Those long-period atmospheric waves that originate with air-streams from the north-west would appear to be related to the interference of one depression with another, and it has been here suggested that they mark the effects of a depression-wave being suddenly dissipated by the counter current of another. Other long-period air-waves, found in the tail-movements of strong surface-currents of air moving over the Cape Peninsula from the south-east, are clearly in a different category, and may originate as standing waves on the lee side of the mountain barrier.

CHAPTER X.

THE ORIGINS OF RANGE-ACTION.

" That reason which is elicited from facts by a just and methodical process, I call Interpretation of Nature."

—— Francis Bacon,
Novum Organum, (1620).

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72. Generation of Sea-Waves by Wind (and Air-Waves).

The argument was advanced in the last chapter (p. 196) that an air-stream, playing over an unobstructed expanse of ocean, and capable of raising sea-waves of widely different periodicities in the visible wave-band (up to 30 secs., say), must itself be influenced by the wave-profile at the common boundary and therefore exhibit near the surface the characteristics of atmospheric waves with equivalent periodicities. Wind-gustiness over water should therefore very largely be in accordance with the orbital oscillations of air-particles, complying with these wave-motions.

It must thus be supposed that there is a natural tendency for the building-up of a joint state of oscillation between air and water when air-currents exert traction on the surface, and the periodicities of such oscillations will be dependent on the average wind-speed.

In Section 39, (pp. 112-116) it was pointed out that within the range of periodicities of visible waves, observers had found the dimensions of the predominant waves to be approximately related to the average wind-speeds. Using Cornish's observations recorded in Table I (p. 114), the wind-speed/wave-period relationship conforms to a straight-line law, as in graph (A) of Fig. 93. Two additional plotted points representing extraneous observations, accord very satisfactorily with this graph: one is an observation of the author's of a series of very pure 2.5

sec. waves which entered the Duncan Dock, Cape Town, under the stimulus of an 8 mph breeze on July 2nd, 1944: the other is from an analysis of waves recorded on Lough Neagh, Northern Ireland, which showed a predominant wave-periodicity of 3.5 secs. in a 15 mph wind[*].

Included in Fig. 93 is a marginal relationship (B) linking maximum wave-periodicity with wind-speed as given by Barber and Ursell[†]. The discontinuity in this relationship is curious, but is probably more apparent than real, for it is likely that the correct limiting relationship follows the trend of (C). This implies that at wind-velocities above about 50 mph there is no longer any restriction (from the wind-generation point of view) on the existence of long-period waves of the invisible ground-swell type.

The very obvious periodicities of several minutes that have been detected in the wind-velocity of the air-currents advancing directly from the open sea upon Cape Town, are evidence, we believe, of surface air-waves that must have had their due influence upon the surface of the sea in promoting the development of long sea-waves of the ground-swell type.

It is probable that near storm-centres, where geostrophic wind-speeds are high, barometric fluctuation becomes an additional factor to that of wind-traction in the generation of waves of all periodicities, but notably long-period ones. The wind-blurring of the microbarogram during high winds, referred to in Section 69 (p. 195), supports this contention.

On theoretical grounds it has been shown by Kelvin and Lamb that a periodically varying surface-pressure applied to the free surface of the ocean will develop a series of expanding

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[*] Barber, 'Ocean Waves and Swell', Published Lecture, Maritime & Waterways Engg. Divn., Inst. C.E., 1950, [91], p. 22.

[†] L.c. (ante p. 114), [64].

waves whose initial and subsequent configurations will be much the same as those of a series of waves deriving from an initial group of equal sinusoidal displacements of the surface of the sea.[*] Fig. 94, which is reproduced from Kelvin's paper, shows the profile of the sea-surface at zero time, and twice subsequently, after equal intervals of time.

The initial displacements divide up into two groups of progressive waves which separate and expand outwards. Points A on the diagrams of Fig. 94 travel at the full wave-velocity corresponding to the individual waves, while points B travel at only half the wave-velocity. It is clear therefore that the bulk of the waves advance at the group-velocity, while long attenuating waves or ground-swells precede the groups. Apparently, perceptible wave-disturbance runs ahead of points A at speeds greater than the wave-velocity, and becomes more important in relation to the group with advance of time.

It seems clear therefore that pressure-variations on the surface of the sea are also to be reckoned with as agencies capable of activating ocean-waves of all types.

Vaughan Cornish, whose painstaking observations of ocean waves have already been referred to (p. 113), describes how on one occasion a band of black cloud overtook his ship when the sea was slight and the wind had dropped[†]. Notwithstanding the fact that only a slight breath of wind accompanied the cloud, the sea was suddenly agitated by a heavy swell. The cloud passed in 5 mins. and in 10 mins. the swell had gone. The inference here is that the swell accompanying the cloud was the direct result of an atmospheric pressure-disturbance.

What must have been a very remarkable instance of the same sort of thing occurred on January 13th, 1948, in the North Atlantic

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[*] Kelvin, 'Initiation of Deep Sea Waves of Three Classes', Math. & Phys. Papers, (Cambridge), 1910, [92], Vol. IV, Paper No. 39, pp. 419-456; Lamb, (l.c. ante p. 105), [54], Art. 195, p. 297.

[†] L.c. (ante p. 113), [60], p.

north-east of New York. 'Death' waves, reputed to be 40 feet high, delayed such large ships as the 'Queen Mary', 'Media' and 'America' on the North-Atlantic run. Commodore Manning of the 'America' (26,300 tons) is reported to have said of this phenomenon:*

> 'About midnight on Tuesday [January 13th] when I thought myself out of the worst of the weather - there had been a series of intermittent gales all the way from the Irish coast - the barometer dropped suddenly. The weather became warmer. The wind dropped - it was blowing only a few miles an hour, but I found myself in huge seas. The ship was lashed from all sides. It was a violent movement of the entire ocean.
>
> 'I reckoned later that this condition covered an area of 600 or 700 miles. I went through it for 12 hours. It was most mysterious. I couldn't understand it - to see such seas with no wind. I had a most depressed feeling at the very experience. Waves usually curl and fall away, but these had no spray'.

The 'America', which was crossing the North Atlantic from the British Isles, bound for New York, would have been head-on to the gales and presumably head-on to the swell following in the wake of the barometric disturbance, to which Manning refers. This disturbance must have been very remarkable and unusual to have affected so large an extent of ocean, and the author would not be surprised if microbarographic fluctuations had been very much in evidence during the whole period of transit of the waves.

73. Pressure Disturbances advancing over Still Water.

On purely theoretical grounds Lamb has shown that a concentrated line-pressure acting upon the surface of a stream of water, of velocity c, will set up a train of standing waves of wave-length $\lambda = 2\pi c^2/g$, on the down-stream side, with amplitudes gradually diminishing according to a law $e^{-\mu x}$, μ being a constant and x the distance from the line of disturbance†. By impressing on everything a velocity $-c$ in the x direction, Lamb

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* Press report, 'Star', Jan. 16, 1948, [93]; also 'Rand Daily Mail', Jan. 17, 1948, [94].

† L.c. (ante p. 105), [54], Art. 243, pp. 400-402.

obtains the effect of a travelling pressure-disturbance advancing with velocity c over still water; namely, a series of waves of diminishing amplitude following in the wake of the concentrated line-pressure. These waves have a wave-length $\lambda = 2\pi c^2/g$ and a periodicity $\tau = (2\pi/g)c$.

When the graph of $\tau = (2\pi/g).c$ is plotted as curve (D) in Fig. 93, it is found to correspond fairly closely with the empirical relationship derived from the observations of Cornish. This suggests that the mechanism of wave-generation by wind is the same in essence as that by a pressure-disturbance advancing with the velocity of the wind. The two cases merge when wind gusts become strong enough to produce identifiable changes of pressure.

The more practical problem of the effects of a series of pressure-pulsations (air-waves, say,) advancing over still water is dealt with by Lamb on the following lines:

> 'If....equal infinitesimal impulses be applied in succession to a series of infinitely close equidistant parallel lines of the surface, at equal intervals of time, each impulse will produce on its own account a system of waves.... The systems due to the different impulses will be superposed, with the result that the only parts which reinforce one another will be those whose wave velocity is equal to the velocity c with which the disturbing influence advances over the surface, and which are (moreover) travelling in the direction of this advance'.*

Lamb proceeds to show mathematically that a wave-train of group-velocity U will be set up by the travelling disturbance. This train will precede or follow the disturbance according as U is greater or less than c.

74. The Front and Rear of a Free Procession of Waves in Deep Water.

In this Section we may consider what happens to a series of simple-harmonic water-waves when the initiating disturbance is withdrawn and the waves are left to themselves to propagate

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* L.c. (ante p. 105), [54], At. 248, p. 413.

into regions of still water.

Kelvin* posed and solved this problem mathematically in a most ingenious way by considering a series of standing waves to the left or negative side of his assumed reference origin, O, in Fig. 95 (a) which is reproduced from his paper. Thus at all great distances to the left of O there would be at zero time ($t=0$) standing waves equivalent to the resultant of two equal trains of progressive waves moving in opposite directions. The rightward component-train would thus tend to invade smooth water to the right of O, while the leftward component-train would recede, leaving still water behind it.

The particular function used by Kelvin to represent the water surface at both front and rear in this way is shown in full-line in Fig. 95 (a): that of a true sine curve is shown in dash-line. The function becomes a true sine curve at about 4 wave-lengths to the left of the origin.

At a time equivalent to 25 wave-periods later ($t=25T$), the wave-front, advancing to the right, assumes the configuration shown in Fig. 95 (b). At the same time the rear of the procession will have distended to the configuration shown in Fig. 95 (c), the latter being the reversed profile of a leftward movement of the tail-end wave-system shown in (a).

The diagrams show that after this particular lapse of time the front of the wave procession has advanced indefinitely with diminishing amplitude, even beyond the distance travelled by a point (A) at the full wave-velocity, while the main body of undiminished sinusoidal waves lies behind a point (B), which has advanced from the origin at a speed of only half the wave-velocity. Point (C) in the rear of the procession has advanced at full wave-velocity; point (D) with half that velocity: the

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* 'On the Front and Rear of a Free Procession of Waves in Deep Water', (l.c. ante p. 210), [92], Vol. IV, Paper No. 36, pp. 351-367.

perceptible rear of the train is thus seen to be lagging about two wave-lengths behind a point advancing with only half the wave-velocity.

The inevitable result of the free movement of a wave-train into undisturbed water is a distension of the overall length of the group with lapse of time. The main group appears to advance at a speed of only half the wave-velocity with the rear lagging somewhat behind this rate of progression, while the front races ahead at speeds varying from half the wave-velocity to infinity. For all practical purposes, however, the important part of the wave-train lies between points which advance at the wave-velocity and half the wave-velocity (cf. also Section 72, p. 210).

A feature of very considerable interest in Fig. 95 (c) is the configuration of the rear of the wave-train, which is seen to exhibit what almost appear to be beat-characteristics. Upon residuating* the main wave-train we find the residual dash-line profile of Fig. 95 (c), which can be further residuated by eliminating what seems to be a small-amplitude wave-train of the same periodicity as the parent-train but with a phase-difference of 90°. The final residual†, shown in dash-dot line, can be traced to the influence of the underlying push-pull wave P-Q which is part of the assumed configuration of both the front and rear end of the original sinusoidal wave-train(Fig.95(a)).

Since any normal wave-train in water, as initially created, must have surfaces of continuity with still water, in front and rear, similar to those adopted by Kelvin at zero time, it follows that at any subsequent time the train of waves will

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* Performed by Chrystal's Method of Residuation (cf. Section 89,p.254 post).

† It is found to correspond exactly with the inverted profile given in Kelvin's Fig. 7, for the case of a single push-pull wave at (l.c. ante p. 213), [92].

be preceded by a series of long expanding waves, and will also be disturbed by the penetration through it from the rear of another series of smaller amplitude, ever-expanding long and short waves.

We are thus able to understand how it is that, in all the examples of Range-action quoted in Section 61 (pp. 170-178) and illustrated in Figs. 77 to 83, the main body of the disturbances with maximum amplitude is not only preceded by long waves but is also transfused by them. Here too we have the explanation to the conundrum posed on p. 117 that ground-swells have been observed to develop after the lapse of winds and the abatement of a storm. Kelvin's analysis shows us that any swell that has passed out of the storm-centre, and continues its propagation without restraint, will of its own accord tend to develop long waves which will be generally interspersed from the front to the rear of the main body of the swell.

75. Tidal Influence on Range-Action

In Section 59 (p. 165) attention was drawn to the fact that Range-action at Cape Town shows a tendency to receive some slight stimulation from the state of the tide, being invariably of somewhat larger amplitude at the flood than at the ebb.

We noted (p. 65) that there is an ever-present seiche-effect outside the harbour even in the calmest weather, making itself felt in a continuous rhythmic breathing of the water in the inner Alfred Basin. It follows from this that there is in the sea at all times an incessant, slow and minute change of level resulting from faint ground-swells arriving on the coast from far afield. For some reason, these gain slightly in magnitude at the high tide, but the effect is most noticeable in the marigrams for the Duncan Basin, which are more particularly suited to the identification of high-frequency Range. One finds that sometimes in fairly calm weather the marigram for this basin will exhibit a slight high-frequency embroidery at high water which will be entirely absent at low water, and that this condition may repeat itself over several consecutive fluxes of the tide.

The obvious explanation which suggests itself is that weak swells, giving rise to this embroidery, are assisted in their propagation towards the coast by the favourable current of the inrunning tide, whereas they are largely annulled when the tidal current reverses and draws off from the coast. Barber and Ursell found a similar effect of the tidal stream upon the apparent periodicity of in-coming waves, and it seems clear that wave-energy can be much reduced or even destroyed by opposing currents*.

The fact that the embroidery (with weak swells) occurs only at slack water on the crest of the tidal wave and not on the rising tide itself when the flux of water into the harbour is at its strongest, must be ascribed to the essential phase difference between tidal streams approaching the coast and those at the head of Table Bay.

Tides tend to co-oscillate by forming seiches where the topography of a coastline is favourable to resonance, as in the bay of Fundy, and this alters the phase of the tide in a bay in relation to what it is at the mouth†. Thus in Table Bay slack water at high tide in the Duncan Basin will correspond with an influx of the tide outside the bay, where weak swells will be aided on their way to the coast; conversely, slack water at low tide at the head of the bay will be synchronous with an out-

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* L.c. (ante p. 114), [64]; cf. also Deacon, (l.c. ante p. 114), [66], p. 234; Barber, (l.c. ante p. 209), [91], p. 17.

† Cf. Sverdrup, Johnson & Fleming, (l.c. ante p. 113), [63], p. 600.

running tidal current off the coast, which will tend to destroy weak, in-coming swells.

76. Waves Originating from a Released Head of Water in a Smooth Sea

Up to the present we have dealt fairly extensively with the various ramifications of Hypothesis a), advanced in Section 62 (p. 178) to explain the origins of Range-action. There remains to consider whether any credence can be attached to Hypothesis b), which envisaged the possibility of ground-swells being born out of the rapid subsidence of the entrained body of water beneath a travelling depression when the latter is suddenly overwhelmed by anti-cyclones, or for other reasons is arrested in its normal progression or development.

The examples 1° and 2° which we examined in Section 60 (pp. 166-170) seemed to suggest that Range-action might be linked with the exhaustion of certain travelling depressions. It has often been noticed, too, that just at the time that depressions are within closest range of Cape Town, the barometric pressure at the Cape suddenly rises instead of reaching new low levels as might be expected. This could result from the depressions encountering colder air-masses in the region south-south-west of the Cape, where their centres of pressure are markedly and suddenly weakened. The question that now confronts us is to know what happens to the elevated body of water in such a set of circumstances.

One factual clue we have lies in an observation of Cornish of the tidal bore on the river Trent in England. He observed the bore advancing in shallow water as a single wave or wall of water, but, upon this entering a region of deep water, it was suddenly transformed into a group of gently rounded swells, whose speed of progression was noticeably less than the speed of the original wave.[*]

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[*] L.c. (ante p. 113), [80], p. 115.

But Kelvin, again, has solved the plane problem for us theoretically and has calculated the surface profile of the sea after successive, equal intervals of time from an assumed zero time, when the disturbance comprised a single, raised body of water, (Fig. 96)*.

The elevated water-mass collapses and divides into two ever-expanding groups of long waves. The progression of particular nodal points in the wave-groups can be followed by the code letters a, b, c, etc., in Fig. 96. The sequence of waves is very like what is seen on a small scale when a stone falls vertically into still water and raises a head of water behind it, namely, antecedent long waves diminishing in length to the perceptible ripples on the innermost ring of expanding undulations.

Although a barometric depression covers a vast area of ocean and the surface-gradient of the elevated water-mass is therefore very slight and perhaps on that account unresponsive to wave development, we have to consider the additional factor, not treated by Kelvin, of a general imposition of pressure suddenly applied upon the raised head of water. It seems conceivable that conditions could arise under an exhausting depression under which the same sort of wave-development as traced by Kelvin could be expected to take place, so that Range-producing waves from such a source might reach the South African coast within a comparatively few hours of a sudden rise in barometric pressure.

77. Sudden Dissipation of Travelling Depressions.

The criterion of such an event taking place would seem to reside in the magnitudes of the rates of change of atmospheric pressure with distance and time at any point of the ocean and at any instant of time. In any direction south of the latitude of

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* L.c. (ante p. 210), [92], Vol. LV, Paper No. 39, pp. 419-438.

Cape Town, barometric pressure can be expected to be less than at Cape Town itself, so that along a radial line in that general direction sea-level has a rising gradient away from the port. The pressure gradient along the radius, $\partial P/\partial r$ thus, in effect, represents the tendency that the sea would have to flow towards Cape Town under the influence of gravity, once the holding-power of barometric suction were removed. It is the rate of change of pressure-gradient with time, $\frac{\partial}{\partial t}(\partial P/\partial r)$, which determines whether this holding-power is altered or not, and the extent of flow in the radial direction towards Cape Town. So long as this quantity is zero no movement will occur, but flow will commence as soon as it is either positive or negative. At some value sufficiently large presumably, propagation will proceed in the form of waves.

Regarding $\frac{\partial}{\partial t}(\partial P/\partial r)$, then, as a measure of the flow towards Cape Town from any point along a particular radial direction, it seems rational to suppose that the ultimate magnitude of the Range-effect which reaches Cape Town from that point will be inversely proportional to its distance r from the port[*]. Hence the quantity $\frac{1}{r}\cdot\frac{\partial}{\partial t}(\partial P/\partial r)$ may be regarded as a criterion of the relative capacity of any particular point in the ocean to be responsible for an observed Range-effect at Cape Town. This quantity, of course, is theoretically infinite when r is zero, and, strictly speaking, some more appropriate factor than $1/r$ should have been adopted to avoid this, but, so long as we agree to limit application of the expression to radii greater than say 200 miles, it should lose nothing of its generality as a sound empirical index of Range-producing potential.

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[*] There is no justification for making this inversely proportional to the square of the distance r, as might be necessary when considering emanation from a point source in all directions in a plane surface, (cf. Lamb, l.c. ante p. 105, [54], pp. 297, 392) since $\partial/\partial t(\partial P/\partial r)$ is already lineal and pertains only to the particular radial line being considered.

The application of this expression in any adequate survey of a wide expanse of ocean, for the purposes of locating the area of origin of supposed ground-swells, is necessarily a laborious task, which the author has had time and opportunity of undertaking in only one case. This was the particular incidence of Range-action of June 19/20th, 1945, already studied in Example 3° (pp. 170-172) in relation to the synoptic charts for the South Atlantic (Figs. 76) and the local conditions at Cape Town (Fig. 77).

Scrutiny of the synoptic charts seemed to indicate that a radial direction south-south-west of Cape Town would afford the most profitable line of enquiry in this quest. This decision was arrived at by plotting first barometric pressures against time, separately for several test points such as 200, 500 and 1000 miles north-west, west and south-west of Cape Town.

Pressure was then plotted against distance along the S.S.W. radial line for each time for which there was a synoptic chart. The pressure gradients, $\partial P/\partial r$, were measured from these curves and plotted against time in a further series of curves, shown in Fig. 97. Extraction of the gradients of these latter curves then yielded values of $\frac{\partial}{\partial t}(\partial P/\partial r)$ at different times, and these were brought to comparative rating by employment of the factor $1/r$ to give, finally, the required quantities for plotting in the Space-Time Chart of Range-Potential, shown in Fig. 98.

Fig. 98 has been contoured to show the magnitude of the 'Range-potential' against a background of distance and time. The red zones in general indicate flow towards, and the blue zones flow away from, Cape Town, and closed or semi-closed contours of high potential suggest the times and distances at which this movement was particularly strong.

It is interesting to find that over the period from June 15th to 23rd there are alternating zones of positive and negative potential indicating a roughly periodic flow to and fro along the radial line at intervals of about 2 days. Some such reversible flow of the sea is clearly necessary to meet the requirements of the rise and fall of the ocean under the travelling depressions and anti-cyclones.

It will be seen that the most likely origins of Range-action in this period occurred on June 15th and 20th at distances of some 200 to 300 miles from Cape Town, when the Range-potental values were respectively 15 x 10^{-5} and 28 x 10^{-5} millibars/sq. mile/day. To see whether these accord in any way with the observed effects at Cape Town, which are reproduced from the weather-chart of Fig. 14(b) on the time axis of Fig. 98, we have merely to project, from the centres and margins of these disturbances on the time-base, lines which conform with the speed of progression of long waves over the depths of ocean directly S.S.W. of Cape Town[*].

The velocity of long waves taken as applicable in this case is that given by equation (8) (p. 108) and the shaded zone of Fig. 27; and the depths of ocean over which they must travel are set forth in Fig. 7. With the logarithmic distance-scale adopted in Fig. 98, it is found that the space-time tracks of such waves may be represented approximately by straight lines.

If there were any reality in the hypothesis we have advanced the space-time tracks of maximum-amplitude Range should pass directly through the centres of high Range-potential in Fig. 96. The peak oscillation for this period occurred in both the Alfred and Duncan Basins at about noon on June 20th, and the space-time track of the long waves necessary to cause such a disturbance is found to pass directly through the zone of maximum Range-potential at a distance of some 200 miles from Cape Town. No better tally could really be desired: moreover the general persistence of the oscillations at Cape Town throughout June 20th and 21st accords

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[*] This final development was suggested to the author by the work of Barber and Ursell, (l.c. ante p. 114), [64], who adopted a similar procedure in examining the origins of short-period swells, which travel at group velocities. In their case the space-time tracks of the waves were successfully related to the geostrophic wind speeds in the storm centres.

well with the considerable commotion in the ocean S.S.W. of Cape Town as portrayed by the closed contours of the red and blue zones.

As against this pleasing congruency, there is a very much less satisfactory tally in the case of the minor peak of Range-oscillation, which occurred at Cape Town at midnight on June 16th. It is, however, what might be called a 'near-miss', and there is some justification for believing that the information in the synoptic charts for that time was not wholly accurate or that the maximum Range-potential occurred on some other radial line nearly but not directly S.S.W. of Cape Town. One feature which supports such a view is that the relative magnitudes of the Range-oscillations for June 16th and 20th are in much the same ratio as the relative values of Range-potentåal for June 15th and 20th in Fig. 96.

It would require many more worked examples of this kind to prove that the apparent truth of our hypothesis was not just a coincidence. All that can be said at present is that there is a strong probability that long ground-swells are set up by the exhaustion of the depressions as a result of the inherent tendency of the sea to accommodate itself to the prevailing atmospheric pressure overhead. To a large extent this movement will be interwoven with the genesis of high winds, since sudden intensification or dissipation of storm-centres will create the conditions most favourable to the promotion of violent geostrophic winds. This is supported by a general observation that can be regarded as an infallible rule: namely, that Range-action of the higher-frequency type, as distinct from the long-period seiches, never occurs but in the company of prominent, visible swells of short periodicity. Seen in this light, our hypotheses a) and b) draw together, (at least in respect of Range-action arising from storms that do not blow home to a port), and the mutations of travelling depressions as the primum mobile of the Range-phenomenon become common to both.

78. Compendium of Knowledge on the Origins of Range.

We are now in a position to gather together the threads of extant knowledge upon the subject of the origins of Range-action and its related phenomena. We shall not at this stage concern ourselves with details of the mechanism of this action, except to note, as in Section 43 (p. 126) and Chapter VII (pp. 129-154), that it may be clearly recognised in its simplest form as an oscillation, seiche or standing wave, formed by the passage through each other of two opposing waves of translation. The fundamental requirement for the development of the phenomenon in a sustained form is that there should exist opposing trains of waves of the same periodicity and of nearly equal energy-content; further that these waves should be of a type that will not readily lose energy on meeting a boundary surface in friction and turbulence of breaking. The particular kind of wave that best complies with these conditions is the ground-swell, and this, by definition in Section 40 (p. 117), is any water-wave whose particle-movements at bed-bottom are at least 80% of the surface-movements. As even the highest-frequency waves become ground-swells in very shallow water (cf. Fig. 27), it is clear that our attention must in the general case be turned upon any source whatever that generates waves in water.

It seems that waves in water, and especially ocean-waves, may derive from any of the following exciting agencies:

(1) Ship movements,
(2) Seismic disturbances,
(3) Meteorological disturbances.

(1). The waves caused by ships when travelling at speed through water, have been shown (p. 93) to include invisible, antecedent swells with periods up to 1 or 2 minutes, besides the more familiar, visible bow-waves and ripples. These long waves precede the ship by considerable distances, and, though feeble, they belong to the persistent ground-swell category; as such, they are capable of generating weak seiches in harbour basins where natural periods of oscillation are of the same order as the in-coming waves.

While no positive connection has ever been established at Cape Town, (and it must be admitted that it has not been sought), between the embroidery on the marigrams and the movements of ships, it is nevertheless possible that the weak oscillations in the Duncan Basin, often observed at high water in fine weather (p. 215), are the result of the near approach of large vessels. Out-running tides tend to destroy weak in-coming swells of this nature and the latter register therefore only when tidal flow is favourable to their propagation (p. 216). Range-action from this source, however, can never be of large proportions, and is really only of passing interest.

(2). More important, but comparatively rare, are the large waves that originate with seismic upheavals, earthquakes, volcanic eruptions and submarine, molar earth-movements. It has been shown (pp. 88-92) that seiches in lakes and large ponds have definitely resulted from earth-pulsations of this kind, and equivalent sea-effects have many times in history been occasioned by submarine shocks or other cataclysmic disturbances (pp. 94-100).

Seismic sea-waves, near their epicentric origin, are usually huge and overwhelming, and even at remote distances they can still be extremely dangerous. It has often been observed that the advent of waves of this type is marked by an initial recession of the sea, followed by three heads of water at intervals of about 15 minutes (p. 96)*. There appears, therefore, to be some natural tendency for seismic sea-waves to be generated always along similar lines.

The only known occasion that waves of this kind have penetrated into Table Bay, is that of the eruption of Krakatoa in 1883 (p. 98). It is more than probable, however, that repercussions of distant tremors have from time to time caused seiches in the bay and harbour, even though no clear-cut instance of this sort has been identified in the ten years that the Range phenomenon at Cape Town has been under study.

(3). Of far greater importance because of their greater frequency are the waves deriving from purely meteorological sources, such as cyclones, hurricanes, frontal depressions, line-squalls, winds and air oscillations. Such waves, that draw energy from the atmosphere, are dependent upon the global circulation of air and the inherent tendency for waves of oscillation to be set up at the interface of two fluid media (air and water), when these move across each other at differing velocities. The very much more mobile atmosphere, in streaming or vibrating over the surface of the sea according to the dictates of hemispherical circulation, induces the oscillation at the surface of discontinuity, known to us as the familiar ocean-wave or coastal seiche.

Wherever wind plays over water, wave-trains are generated in which the most conspicuous wave-periodicity appears to be proportional to the wind-speed (pp. 114, 209), and the maximum to be about 4/3 of this predominant one. But purely wind-generated waves of periodicities above about 30 seconds cannot exist owing to the general theoretical and observational condition that speeds of wind-generated waves be always less than wind-speeds

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*Cf. also Green, (l.c. ante p. 100), [46], p. 4.

(80%, according to Cornish, p. 114). Waves of higher periodicity than 30 seconds have speeds in deep water exceeding 150 mph (Fig. 27), which is more than any known wind-velocity.

It has been noticed that when the predominant wind-speed exceeds about 50 mph, there no longer seems to be any restriction upon the maximum periodicity of wave occurring in the resultant wave-train (p. 209). This suggests that some other factor comes into operation with high winds to extend the scope for generation of long waves and ground-swells, known to accompany wind-generated waves (p. 118). The most obvious agency is barometric pressure and this introduces consideration of the oscillatory nature of atmospheric circulation.

The atmosphere has been shown to envelop the world in a series of ellipsoidal, isentropic shells, co-axial with the earth's poles (p. 181), and the intrinsic resiliency of these layers is responsible for the phenomenon of air-waves (p. 182). In particular, the large air-waves which form at the polar-front discontinuity between the layers over the hemispherical temperate zones, are the media mainly responsible for weather. The travelling depressions of these regions appear to be the vortices created by the breaking of these eastbound waves along the latitudes where the discontinuity intersects the globe (p. 183); as such, they are the centres of disturbance over the sea which give rise to the most violent winds and which constitute the most important sources of ocean-waves. Cyclones and hurricanes are less frequent, but more vigorous, examples of the same sort of thing occurring in the equatorial belt, and are more especially to be feared for the seismic-like sea-waves they are capable of developing (p. 118).

We have attempted to show that line-squalls, which invariably accompany the cold-front of a travelling depression, are themselves parasitic waves riding on the back of the parent depression-wave (p. 191). They appear to bear some resemblance to bores in estuarine waters, and run down the cold-front interface to break in gusts of wind and rain on the surface of the earth or sea. The cold-front and line-squalls are definite pressure-surges, which on their own account will induce trains of sea-waves during their forward progression across the ocean (p. 211). The waves, so engendered, will precede or follow in the wake of the disturbing line of pressure, according as the group-velocity is greater or less than the speed of the pressure wave (p. 212).

But cold-fronts and line-squalls, which must be rated as long atmospheric waves, are not the only types of air-waves which, barometrically, are capable of influencing the surface of the sea. Evidence has been adduced in preceding pages to show that the travelling depressions are invested with still smaller atmospheric waves, which react on the wind by giving to it much of its intermittent gustiness (p. 192). The reality of these air-waves is often proved by simultaneous periodic fluctuations of barometric pressure and wind-strength, but the height of the wave-plane and the wavelength of the aerial billows seem to determine whether they will register barometrically at all (p. 196).

There can, nevertheless, no longer be any doubt but that these quasi-periodic fluctuations of pressure and wind-velocity, when impressed upon the surface of water, induce long ground-swells capable of causing both lacustrine and marine seiches and the smaller vibrations of lake or sea, known variously as scend, surge, run, undulation, surf or Range (pp. 86, 103, 210).

The question of how these ocean-waves would be disposed in relation to the moving cold-front of a depression is of some interest Here we may note that depressions and their cold-fronts advance at speeds of about 35 to 40 mph (pp. 163, 185), while line-squalls and following winds in the average case pass through them at speeds of perhaps 45 to 50 mph (p. 191). On the basis of the observation that wave-velocities tend to be of the order of only 80% of the wind-velocities, the bulk of the purely wind-generated waves could be expected to have speeds in deep water of the order of 36 to 40 mph, corresponding to predominant wave-periodicities between 10 and 15 seconds (Fig. 27). In deep water these waves would advance with a group velocity only half that of the individual waves, say 20 mph, and would thus tend to lag behind the cold-front. Long waves of periods above about 30 seconds, on the other hand, if induced by barometric oscillations at or near the cold-front, would travel in deep water at the high speeds of ground-swells and would rapidly out-distance the front. As the waves became retarded on a shelving coastline, the cold-front would tend to gain upon them again to a limited extent. We should thus expect to find long waves precursing, and short waves trailing, the cold-front, although this arrangement would not be inflexible, and would depend very largely on where the highest winds and most pronounced barometric oscillations were situated in relation to the front.

We find some measure of support for this conception in the detailed examples of Range-action considered in Chapter VIII. In the specific cases 3°, 4° and 5° (pp. 170-175), wherein the storms blew home to the port and the cold-fronts were identifiable, the long-period seiches are found to have preceded the arrival of the cold-fronts by approximate periods of 8, 36 and 24 hours, while the main body of the shorter-period Range-action lagged behind by some 27, 21 and 14 hours respectively. But here it must be remarked that even this sequent Range-action derived from long ground-swells, so that our generalisation of wave-positions with reference to the storm requires qualifying in respect of the likelihood that the main body of ground-swells originates from the depression-centre itself - the hub of activity, which may be many hundreds of miles away from the particular point of the cold-front being considered.

Here we must consider the possibility that a further agent in the development of long ground-swells is the release of the entrained body of water at the core of a depression as the result of sudden exhaustion of barometric suction, and plunger-like action on the surface of the sea from the inrushing anti-cyclone (p. 217). Some brief study of this aspect with rather limited data suggests, nevertheless, that this may be an important contributing factor (p. 222). Ground-swells in this case would develop from the gravitational flow of a raised head of water expanding into still water, (p. 218).

We have not yet exhausted the possible modes of excitation of long ground-swells accompanying wind-generated waves, for it appears that they are in any case the necessary accompaniment of a free procession of waves in deep water (p. 213). Any group of waves, whipped up by the wind, which passes out of the storm area and is left to its own devices to propagate as a smooth swell, will,according to the theoretical predictions of Kelvin, gradually attenuate itself by developing antecedent ground-swells advancing through the group from the rear (p. 215). Theory shows that this happens also in all the modes of generation of water-waves we have thus far considered, whether it be from wind, pressure-fluctuation, initial surface-elevation or advancing steady pressure (pp. 209, 211, 213, 218).

The pattern of Range-action begins to assume a semblance of uniformity, and the observation that swell always accompanies Range-action fits naturally into the picture we have formed of the affinity ground-swells have for any type of wave propagation. It seems that our original visualisation of concurrent influences may not be far removed from the truth, Range-action in any given instance being born of surface-winds, barometric oscillations, advancing aerial bores or billows, and vanishing depressions, all operating together to produce overlapping effects of a similar kind, although each by itself could produce the action independently of the others.

There remains, however, to draw the distinction between meteorological effects which excite powerful long-period seiches in the absence of observable swells from the sea, and those we have just considered, which are more particularly responsible for the dense embroidery on marigrams. The former has been shown to consist of vigorous barometric oscillations, prevalent directly over the coastal area at the time the seiches develop and comparable in periodicity with the induced seiches, (pp. 145, 201-203).

At present no very clear-cut relationship of these barometric oscillations to the weather has been established, but there seem to be some grounds for believing that they may originate from the general mêlée of opposing air currents destroying each other's momentum, or from one depression-wave overtaking and overriding another (p. 204).

In the case of Table Bay the development of these seiches appears to be dependent on a north-westerly drift of the atmosphere overhead and it is likely therefore that extremely long waves enter the bay from the open ocean in addition to the forced waves created directly under the air-disturbances.

PART IV

THE
ANALYSIS
OF
RANGE - ACTION

" All motion propagated through a fluid diverges from a rectilinear progress into the unmoved spaces".

—— Isaac Newton,
Principia Mathematica, Book II, (1686).

CHAPTER XI

THE HYDRODYNAMICS OF SEICHES

> " One of the most interesting and successful applications of hydrodynamical theory is to the small oscillations, under gravity, of a liquid having a free surface''.
>
> —— Sir Horace Lamb,
> Hydrodynamics, (1879).

79. Seiches. Standing Waves and Range-action.

In Section 30 (p. 84) we drew attention to the phenomenon of seiches in lakes which Forel had recognised as being oscillations of the entire water-mass, although comprising in effect opposing, progressive waves of oscillation travelling through each other and returning from end to end of the lake.

From bibliographical researches and our own observations and investigations at Cape Town dealt with in Parts II and III, it is clear that the oscillations and vibrations of the sea, commonly found in semi-enclosed harbours, bays and inlets, or even upon open coasts, are manifestations of the same phenomenon of standing waves, essentially the result of the interpenetration of reflected ground-swells and their still-incoming followers.

Some study of the theoretical implications of this transfusion of opposing waves is necessary to a perfect understanding of the Range phenomenon, and we pursue this aspect therefore in what follows.

80. Properties of Standing Waves.

In Section 37 (p. 107) we gave some of the theoretical derivations applicable to progressive oscillatory waves whose amplitude, A , was small compared with their wave-length, λ , and the depth, d , of water through which they travelled. The underlying theory* which gave rise to the results quoted in

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*Cf. Lamb, (l.c.ante p.105),[54],Arts.227-228,pp.363-366;also Sverdrup, Johnson & Fleming,(l.c.ante p.113),[63],pp.516-604;Milne-Thomson, 'Theoretical Hydrodynamics',(London),1938,[95],pp.354-359.

equations (1) to (9) for progressive waves, is really fundamental to the case of standing waves in a uniform depth of water, for which latter the comparable equations of component displacements (ξ , η) of water-particles in the horizontal and vertical directions at any point (x , z) are:

$$\left.\begin{array}{ll} \text{(i)} & \xi = -A\dfrac{\operatorname{Cosh} q(z+d)}{\operatorname{Sinh} qd}.\operatorname{Sin} qx.\operatorname{Sin}(pt+\epsilon)\ \text{(horizontally)} \\[2ex] \text{(ii)} & \eta = A.\dfrac{\operatorname{Sinh} q(z+d)}{\operatorname{Sinh} qd}.\operatorname{Cos} qx.\operatorname{Sin}(pt+\epsilon)\ \text{(vertically)} \end{array}\right\} \text{——(14)}$$

As before, the system of standing waves is referred to the vertical plane XOZ, whose origin O lies in the undisturbed surface of the water, the OX axis being horizontal and the OZ axis vertical and positive upwards. In equations (14), p and q are respectively the periodic and nodal frequencies defined in equations (2) and (3), (p. 107), and ϵ is an arbitrary phase angle.

In Fig. 99 we reproduce Lamb's illustration which is typical of the oscillating system of a standing wave in a uniform depth of water. The lines beneath the surface-profile ABCDE represent the general directions of motion to which the particle displacements are tangential. Water-particle movements are all rectilinear and simple-harmonic, motion under the crests C being everywhere vertical, and under the nodes B and D everywhere horizontal. The surface-profile ABCDE is given by equation (14)-(ii) when $z = 0$ and $\operatorname{Sin}(pt+e) = 1$, namely, $\eta = A.\operatorname{Cos} qx$: the dash-line profile A'BC'DE', on the other hand, is the surface-profile ($z = 0$) half-a-period later, when $\operatorname{Sin}(pt+e) = -1$ and the vertical displacements in the surface are everywhere $\eta = -A\operatorname{Cos} qx$. At any other times except those which are multiples of half-wave periods, the vertical displacements η are less than those shown by the limiting profiles ABCDE and A'BC'DE', but are subject to the condition that at all times the vertical movements at the nodes B and D are zero, and, on the two sides of a node, of opposite phase. At a point in time equidistant between the extreme profiles ABCDE and A'BC'DE', the surface of the water will be momentarily a straight line.

As the hyperbolic factors in equations (14) are identical with those of equation (9), the same remarks apply (p. 108); namely, that for long standing waves for which λ is large compared with d, the horizontal movements of water, ξ, are sensibly the same at all depths. A long seiche or standing wave is thus characterised by a solid mass-movement of water horizontally at the nodes which diminishes steadily as the direction of movement changes to the vertical rise-and-fall of water at the antinodes or ventral loops of the oscillation.

By superimposing two identical systems of standing waves, displaced relative to each other by a phase-difference of a quarter of the period, so that the antinodes of the one system overly the nodes of the other, we obtain a train of progressive oscillatory waves with the properties already discussed in Section 37[*]. Further, by superimposing two identical trains of such progressive waves, travelling in the opposite directions of x negative and x positive, we arrive at a system of standing waves, having the same wave-length and period but double the amplitude (at the antinodes) of the component waves[†].

81. The Energy of a system of Standing Waves.

The energy contained in a system of standing waves obviously comprises the potential energy of elevation and the kinetic energy of particle-motion. It can be shown[§] that the amounts of each of these per wave-length per unit width of standing wave are respectively

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[*] Lamb, (l.c. ante p. 105), [54], Art. 229, p. 366.
[†] This is well demonstrated by Darwin, (l.c. ante p. 38), [28], p. 37.
[§] Lamb, (ibid), [54], Art. 230, p. 369.

$$\tfrac{1}{4} g\rho A^2\lambda . \operatorname{Sin}^2(pt+\epsilon) \quad . \ . \ . \ \text{(potential)}$$

and

$$\tfrac{1}{4} g\rho A^2\lambda . \operatorname{Cos}^2(pt+\epsilon) \quad . \ . \ . \ \text{(kinetic)},$$

making the total energy per wave-length of standing wave

$$E_s = \tfrac{1}{4} g\rho A^2\lambda \quad . \qquad (15)$$

The only symbol not hitherto appearing is ρ , the density of the fluid medium.

For a system of progressive waves of simple-harmonic form the amounts of potential and kinetic energy are found to be exactly equal, and the total energy per wave-length per unit width in their case is:

$$E_p = \tfrac{1}{2} g\rho A^2\lambda \quad . \qquad (16)$$

If two identical trains of progressive waves, each carrying the energy content of (16), travel in opposite directions through each other, their combined energies per wave-length per unit width will amount to $g\rho A^2\lambda$. This may be written in the form $\frac{1}{4} g\rho(2A)^2\lambda$, the energy of the resultant standing-wave system, as in (15), from which it is clear that the amplitude of the standing waves will be double that of the component progressive waves.

This circumstance explains how it is that long ground-swells of small amplitude in the open ocean just outside an oscillating area, such as a bay or harbour, are able to develop in amplitude as standing waves or seiches, through the energy contribution of their reflections. Apart from this, of course, there is a natural tendency for the amplitudes of the incoming waves to increase as a result of the diminishing depths over which the waves travel in their approach to a coastline.

The implications of this last statement may be examined in the case, say, of long waves by replacing λ in equation (16) by the use of equations (5) and (8), (pp. 107, 108). The energy of the progressive waves then becomes $E_p = \frac{1}{2} g \rho A^2 . \tau . \sqrt{gd}$, from which it is seen that the energy is proportional to the square of the amplitude and the square root of the depth; that is,

$$E_p \propto A^2 . \sqrt{d} \qquad \text{\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_} (17)$$

If the energy of long waves remained substantially unaffected by frictional losses, we could expect from (17) that the amplitude of the waves would vary inversely as the fourth root of the depth*: in actuality, however, the frictional losses cannot altogether be ignored†, and the increase in amplitude of the waves with diminution of the depth of water would fall rather short of this.

82. Free Oscillations or Seiches in Enclosed Basins.

A seiche may be considered as a particular case of a standing-wave system which is 'tuned' to the dimensions of the oscillating area in which it is set up. As such, it becomes in effect a series of resonant standing-waves, because the reflections of the underlying constituent waves form a further standing-wave system on their own which synchronises exactly with the parent one and augments it. The reflections of the reflected waves repeat this process, and in theory, were it not for the fact that there is always frictional damping to absorb the energy of the waves, the amplitude of the ultimate resultant standing-waves would become infinitely great.

In the simplest case of an enclosed rectangular basin of uniform depth, d , the free oscillations of the water-body must obviously be such as to make the horizontal displacements ξ at the two ends zero, since the boundary conditions make such horizontal movement impossible. The conditions that $\xi = 0$ at $x = 0$ and $x = L$, where L is the length of the basin, are fulfilled if $\sin qx$ in equation (14)-(i) is zero when x has these values:

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* When convergence of the wave-frontage is also taken into account in (17), we arrive at Green's Law that $A \propto b^{-\frac{1}{2}} . d^{-\frac{1}{4}}$, where b is the breadth of the wave-front (cf. Lamb, l.c. ante p. 105, [54], p. 275).

† Cf. Stanton, 'Friction', Glazebrook's Dictionary of Applied Physics. (London 1922, [96], Vol. I, pp. 372-375.

that is, if $q L = m\pi$. ——————(18A)
where m is an integer having possible values 1,2,3,... By substituting for q in terms of equation (3), and by further use of equations (5) and (8), we arrive at the periodicity of the free oscillation in the basin, namely,

$$\tau_m = \frac{1}{m}\cdot\frac{2L}{\sqrt{gd}}\ ^{*} \qquad \text{.} \text{——————(18).}$$

In the slowest mode of oscillation ($m = 1$), the seiche is uninodal with the node in the middle of the basin and the adjacent opposing antinodes at the two ends. The water thus rocks or seesaws about the node, and the period of the oscillation is the period of its component progressive waves which have a wave-length twice the length of the basin (cf. p. 85). The higher modes of oscillation have periods ½, 1/3, ¼,... of the fundamental uninodal seiche, and their number of nodes corresponds to the value of m . In general a complete harmonic series of seiches can exist, the binodal, trinodal and multinodal seiches adding to the overall movements.

When we come to consider two-dimensional propagation in a rectangular basin of uniform depth, the modes of oscillation are given by τ in the following[†]:

$$\left.\begin{aligned} &\text{(i)} \quad \frac{4L^2}{\tau^2 gd} = m^2 + \frac{n^2}{\beta} \\ &\text{where} \\ &\text{(ii)} \quad \beta = \left(\tfrac{B}{L}\right)^2 \end{aligned}\right\} \text{——————(19)}$$

and L and B are respectively the length and breadth of the basin, n being an integer of possible values 0,1,2,3,... By taking $n = 0$, we obtain the same result as (18) for the component oscillation in the direction of the length. If a pure transverse oscillation were possible in the direction of the breadth, it could be expected to have a period given by (19) when $m = 0$; but in general, if L is much greater than B , such a transverse seiche will be unstable and the true condition will be given by (19) when longitudinal and

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[*] The original derivation of this formula has been attributed to Merian (1828) (lo.ante p. 113), [63].

[†] Cf. Lamb, (l.c. ante p. 105), [54], Art. 190, p. 284.

transverse influences are at work together.

The conditions of a variable width and depth of basin or lake require separate treatment[*]. The general case has been solved by Chrystal[†], who applied his theory to calculating the natural periods of oscillation of different lakes, of section and shape both uniform and irregular. The measure of his succe lies in the fact that he was able to obtain remarkably close theoretical tallies with observed periodicities for such lakes as Constance, Garda, Madüsee, Neuchâtel, Starnberg, Geneva, Ness and Earn, and also for particular configurations of basins adopt ed in model experiments[§].

A point of some interest to us in our later consideratio of the seiches in Table Bay, is the fact, discovered by Chrystal that in lakes of variable depth, the periods of the successive modes of oscillation do not in general conform to the harmonic series 1, ½, 1/3, ¼,.... Thus in a rectangular lake of paraboli longitudinal cross-section, whose maximum depth is d_0, the periods τ_m of free oscillation are given by

$$\frac{\pi^2 L^2}{\tau_m^2 \cdot g d_0} = m(m+1)\,{}^{‡}, \quad \text{\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_} (20$$

which, for the uninodal, binodal,....seiches, are then in the rati os 1, 1/1.73, 1/2.45,....

In the case of a rectangular lake whose longitudinal cross-section is of the shape of part of the quartic curve, namely, $z = d_0\left(1 - \frac{4x^2}{L^2}\right)^2$, d_0 being the maximum depth, the resonant periods τ_m conform to

$$\frac{\pi^2 L^2}{\tau_m^2 \cdot g d_0} = \frac{\psi^2}{4}\left(\frac{4m^2\pi^2}{k^2} + 1\right)^{**} \quad \text{\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_} (21)$$

where ψ and k are quantities dependent on the configuration of the lake. It is entirely possible in a lake of this concave shape for the trinodal seiche to have a period only half of the

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[*] Cf. Lamb (l.c. ante p. 105), [54], Arts. 185-186, pp. 273-277.

[†] L.c. (ante p. 84), [41], pp. 599-649.

[§] White & Watson, 'Some Experimental Results in Connection with the Hydrodynamical Theory of Seiches']Proc.Roy.Soc.Edin.,1906,[97],Vol.26,p.142-156.

[‡] Ibid,[41]; also Lamb (ibid),[54],p.277.

[**] Ibid,[41].

uninodal seiche, the ratios of the periods running as 1, 1/1.46, $\frac{1}{3}$, ... Lake Constance was found by Forel to exhibit periods for the uninodal, binodal and trinodal seiches very close to this series.

According to Chrystal's findings, equation (21) has wide applicability with good approximation to a large number of natural lakes. If the periods τ_1 and τ_2 of the two longest modes of oscillation are known from observation, the others can be computed from the formula

$$\tau_m = \tau_1 \sqrt{\frac{1+j}{m^2+j}} \text{[*]} \qquad (22)$$

in which (i) and (ii)

$$\left.\begin{aligned} &\text{(i)} \quad j = \frac{4-R^2}{R^2-1} \\ &\text{and} \\ &\text{(ii)} \quad R = \tau_1/\tau_2 \end{aligned}\right\} \qquad (23)$$

More important to us from the point of view of their approximation to the shape of Table Bay (cf. p.40 and Fig. 8) are enclosed basins of circular or elliptic shape.

The free oscillations in a circular basin of diameter D, having a paraboloidal bed whose depth at radius r is $z=d_0\left(1-\frac{4r^2}{D^2}\right)$, d_0 being the maximum depth at the centre, have been investigated by Lamb[†]. He found the symmetrical modes, in which water oscillates about nodal circles, to be given by

$$\left.\begin{aligned} &\text{(i)} \quad \frac{\pi D}{\tau_m\sqrt{gd_0}} = 2.828,\ 4.899,\ 6.928,\ 8.94,\ 10.94, \\ &\qquad\qquad\quad 12.95,\ 14.96,\ldots. \\ &\text{and the unsymmetrical modes by} \\ &\text{(ii)} \quad \frac{\pi D}{\tau_m\sqrt{gd_0}} = 1.414,\ 3.742,\ 5.831,\ 7.865,\ 9.88, \\ &\qquad\qquad\quad 11.92,\ 13.93,\ldots. \end{aligned}\right\} \qquad (24)$$

The first mode in the unsymmetrical class is a pure uninodal seiche about a diameter, in which the water simply sways from side to side: the second mode contains both a nodal diameter and a single nodal circle. The ratios of the periodicities, representing alternate unsymmetrical and symmetrical modes of

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[*] L.c. (ante p. 84), [41].

[†] L.c. (ante p. 105), [54], Art. 193, pp. 291-293.

oscillation, form the series 1, $\frac{1}{2}$, 1/2.65, 1/3.46, 1/4.12, 1/4.90, 1/5.56,....

An approximation to the slowest mode of oscillation in an elliptic basin of uniform depth d, whose boundary-equation is $\frac{x^2}{L^2} + \frac{y^2}{B^2} = \frac{1}{4}$, is given by Lamb as*

$$\left.\begin{array}{ll} \text{(i)} & \dfrac{\pi^2 L^2}{\tau^2 g d} = 3 + \dfrac{3}{5+2\beta} \\ \text{where} & \\ \text{(ii)} & \beta = \left(B/L\right)^2 \end{array}\right\} \text{———————} (25).$$

and L and B are respectively the major and minor axes of the basin.

The problem of the free oscillations in an elliptic basin with a paraboloidal bottom of maximum depth d_0 has, however, been solved by Goldsbrough†, whose results for the principal modes reduce to

$$\left.\begin{array}{ll} \text{(i)} & \dfrac{\pi^2 L^2}{\tau^2 g d_0} = 3 + \dfrac{1}{\beta}\left\{3 \mp \sqrt{4\beta + 9(1-\beta)^2}\right\} \\ \text{(ii)} & \dfrac{\pi^2 L^2}{\tau^2 g d_0} = 2 \\ \text{(iii)} & \dfrac{\pi^2 L^2}{\tau^2 g d_0} = 10 + \dfrac{1-\beta}{\beta}\left\{3 \pm \dfrac{1}{1-\beta}\sqrt{16\beta^2 + 9(1-\beta)^2}\right\} \\ \text{(iv)} & \dfrac{\pi^2 L^2}{\tau^2 g d_0} = \dfrac{2}{\beta} \end{array}\right\} \text{———————} (26)$$

Equation (26)-(i) has two solutions, the lower frequency of which is a mode of oscillation occurring about a pair of nodal hyperbolas. The other solution refers to an oscillation about a nodal ellipse. Equation (26)-(ii) represents a pure seiche in which the water surface remains plane while rocking about the minor axis as node. The two solutions of (26)-(iii) give in the lower frequency an oscillation about the minor axis

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* L.c. (ante p. 105), [54], p. 290.

† 'The Tidal Oscillations in an Elliptic Basin of Variable Depth', Proc. Roy. Soc. Lond., Vol. A 130, 1930, [98], pp. 157-167.

and two nodal hyperbolas, and, in the higher frequency, about the minor axis and a nodal ellipse. The fourth result refers to a simple oscillation about the major axis, in which the water-surface remains plane as it rocks.

The particular value of the ratio B/L of most interest to us is 2/3, this being about the ratio of the axes of Table Bay, regarded as an elliptic bowl (p.40). For a value of β, then, of 4/9, equation (25) gives

$$\frac{\pi L}{\tau\sqrt{gd}} = 1.873 \qquad (27)$$

while equations (26) reduce to a series

$$\frac{\pi L}{\tau\sqrt{gd_0}} = 1.414,\ 2.121,\ 2.225,\ 2.875,\ 3.816,\ 4.387,\ldots. \qquad (28)$$

Since d in (27) refers to a basin of uniform depth, while d_0 in (28) applies to the maximum depth of an ellipsoidal basin, the two results are not directly comparable.

Equations (26) should give identical results to (24) for the special case when B and L are equal and the ellipse becomes a circle. Making $\beta = 1$, we find from (26)

$$\frac{\pi L}{\tau\sqrt{gd_0}} = 1.414,\ 2.000,\ 2.828,\ 3.162,\ldots. \qquad (28A)$$

The principal modes of symmetrical and unsymmetrical oscillation in (28A) agree with (24), but Goldsbrough's other figures (2.000, 3.162) are unidentified. We shall, nevertheless, at a later stage assemble all these results for comparison with the observed periodicities of seiches in Table Bay.

83. Forced Seiches in Enclosed Basins.

Although the basins we have to deal with in gulfs, bays, inlets and harbours are seldom fully enclosed, they are nonetheless subject to much the same effects as are found in landlocked bodies of water, and the extended study of the latter, therefore, is fully justified by the information we can gain.

Up to the present we have considered only the free oscillations of enclosed bodies of water, which reveal the modes in which the water would sway by natural inclination as dictated by the topographical features of shape and depth. If disturbing forces of periodic nature are applied, seiches of precisely the same nature as the free oscillations will be set up provided that the frequencies of the periodic forces agree with the natural frequencies of the particular basin considered. Certain peculiarities are often exhibited in forced oscillations by the failure of the exciting force to stimulate the even modes of the free oscillations and this circumstance merits some examination.

In the case of a rectangular basin of uniform depth, it will be found that under the uniform stimulus of a periodic horizontal force, $X = f. \cos(pt+\epsilon)$, such as might represent tide-generating forces in a landlocked sea, it is only the odd-modes of oscillation which are excited when the applied periodicities are given by equation (18) for $m=1,3,5,\ldots$.[*] The explanation for this lies in the fact that the impressed force, which is horizontal, cannot synchronise with the vertical motion of the water in the middle ventral loops or antinodes of even-modes of oscillation, which are always central in the length of the basin.

Chrystal was disposed to recognise the existence of forced seiches as being set up by violent storms on inland lakes[†]. In general the seiche-periods recorded during such storms were found to be irregular, as if composed of a jumble of seiche components, differing somewhat from the true seiches which developed after the storms lulled. We may hazard an explanation for this on the basis of the knowledge we have gained

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[*] Cf. Lamb, (l.c. ante p. 105), [54], Art. 179, p. 266.
[†] L.c. (ante p. 84), [41].

in the earlier part of this work. It seems clear that a storm in passing over a lake will generate, as it does over the ocean, a complex system of wave-trains, some of whose periodicities may agree more or less closely with the natural periods of the lake. Those impressed periodicities which happen to lie closest to the natural periods of the basin will tend to generate forced seiches in virtue of the wide frequency-band of response, on either side of the critical resonant frequency, that a lake or basin usually has. Examples of this in the case of Table Bay harbour will be demonstrated in later chapters.

84. Seiches in Semi-Enclosed Basins Linking with the Sea.

We come now to consider the forced oscillations set up in basins which communicate with the open sea, as a result of the ingress of ocean-waves.

The problem in its simplest form consists in analysing the standing-wave system induced in a rectangular canal of uniform depth d, closed at one end, at a distance L from the mouth fronting on the sea*. If sea-level at the entrance of the canal is subject to a periodic vertical displacement $\eta = A.\text{Cos}(pt+\epsilon)$, the condition must be met that the standing waves in the canal have this value for η when $x=L$, (taking the origin at the end of the canal). For equation (14)-(ii) to conform, we must therefore have

$$\eta = A.\frac{\text{Cos}\, qx}{\text{Cos}\, qL}.\text{Cos}(pt+\epsilon)$$

For all values of q which make $\text{Cos}\, qL = 0$, this solution fails through η becoming infinitely great; the critical condition bringing about resonance is, therefore

$$qL = s.\frac{\pi}{2} \quad ,$$

where s is an odd integer of successive values 1, 3, 5,.... By the same process of derivation as for equation (18), this

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* Cf. Lamb, (l.c. ante p. 105), [54], p. 267.

leads directly to the result

$$\tau_m = \frac{1}{s} \cdot \frac{4L}{\sqrt{gd}} \qquad (29)$$

The slowest mode of resonant oscillation ($s=1$), in contradistinction to that occurring in an enclosed basin (p237), now takes place about a node which lies across the mouth of the canal. The fundamental oscillation therefore consists of just half of the ventral loop of a standing wave (Fig. 99), with the antinode at the head of the basin. The next mode has two nodes, one of which lies at the entrance, and one-and-a-half ventral loops in the resulting seiche. The periods of all the possible modes of oscillation have ratios in the harmonic series 1, 1/3, 1/5,.... and the number of nodal lines corresponds to $\left(\frac{s+1}{2}\right)$, of which one lies always at the entrance.

We have here another example of the suppression of even modes of oscillation, but at first sight the position looks anomalous in view of the fact that sea-level at the canal mouth, in terms of our premises, rises and falls in a forced oscillation $\eta = A.\cos(pt+\epsilon)$, whereas, in terms of resonance, no vertical displacement is possible at the entrance-node. However, the difficulty is resolved when we realise that the seiche is the resultant of the impressed pulse and its reflected wave.

If the rectangular basin or canal we have considered is now given a shelving bottom from maximum depth at the entrance to zero at the end, the incoming waves are fore-shortened as to wave-length and stimulated as to amplitude. On the other hand, if the basin converges towards its head without change of depth, the height of the waves is increased without much change of wave-length. The combination of converging sides and shelving bed is a type of basin commonly found in estuaries and coastal inlets, and the mathematical solution of the surface profile of the oscillation has been found to apply with fair approximation to co-oscillating tides in such places, notably the Bristol Channel*.

The first two of the above three cases are of special interest to us. In the case of the rectangular canal with straight sloping bed, open to the sea at one end, Lamb gives the solution to the free surface, as the result of a forced oscillation of amplitude A, outside the canal, as

$$\eta = A\left[1 - \frac{Kx}{1^2} + \frac{(Kx)^2}{1^2.2^2} - \frac{(Kx)^3}{1^2.2^2.3^2} + \cdots\right]$$

which is the equation of a Bessel function, $A \cdot J_0(2K^{\frac{1}{2}}x^{\frac{1}{2}})$, where $K = \frac{p^2 L}{gd}$ and p is defined as in equation (2).

As this series converges rapidly for ordinary values of Kx, it suffices to neglect higher powers than the square, and express the condition for the first mode of oscillation in the canal, (that the node lie at the mouth), by equating $\eta = 0$ at $x = L$, the length of the basin. This gives $KL = 2$, or

$$\frac{4\pi^2 L^2}{\tau^2 . g d_0} = 2 \qquad , \text{\_\_\_\_\_\_\_\_\_\_\_\_} (30)$$

approximately, where d_0 is the maximum depth of the bed at the mouth. This result, it may be noted, is the same as for a rectangular basin of length $2L$ with parabolic bed of maximum depth d_0, as given by equation (20).

For a triangular canal of length L and uniform depth d, open to the sea at the broad end, Lamb shows the equation of the free surface to depend on the Bessel function $J_0(kx)$, where $k = p^2/gd$. Again the condition that a node always lie at the mouth of the canal, (for which $J_0(kL)$ must be zero), is satisfied when

$$\frac{\pi L}{\tau\sqrt{gd}} = 1.20,\ 2.76,\ 4.33,\ 5.87,\ 7.45,\ 9.05, \text{\_\_\_\_\_\_} (31)$$
$$10.63,\ 12.23,\ 13.82, \ldots.$$

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* Cf. Lamb, (lo. ante p. 105), [54], Art, 186, p. 276.

Bays and gulfs of semi-circular, semi-elliptical, or irregular shape are forms of basins which are less amenable to mathematical treatment. The Japanese investigators, Honda, Terada and Isitani, made some attempt to investigate particular cases[*], but it seems that the most satisfactory approach to the problem of irregular shapes lies in Doodson's and Defant's grapho-mathematical methods of analysis[†]. The author learnt of these too late to permit of calculations being made or this basis for Table Bay, but he applied other methods, (to be described), to achieve the same end.

The transverse oscillations in a flume of water of triangular section are of some interest to us insofar as, by the mathematical device of transferring the origin to one edge of the canal in the general problem, and of making the breadth infinite, we obtain a system of standing waves on the shelving bed of a sea terminating at a coastline[§]. A point of some significance is that the standing wave system accords with a complete reflection of the incident waves, although there is some change of phase. It is therefore clear that standing waves from groundswells are as much a feature of sloping beaches as of canals or basins of uniform depth, and it requires only some slight variation of submarine topography, such as undulations of the sea bed, for the development of resonant standing-waves or seiches on open coasts. In this connection it is of interest to record that seiches of 15 minutes period have been detected off the straight coastline near Atlantic City in the United States[‡].

85. The Phenomenon of Beats in Standing Waves or Seiches.

In Section 38 (p. 111), we referred to the tendency of

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[*] L.c. (ante p. 102), [48].

[†] Cf. Sverdrup, Johnson & Fleming, (l.c. ante p. 113), [63], Chap. XIV; Doodson, Trans. Roy. Soc. Edin., Vol. 52, 1920, [99], p. 629.

[§] Lamb, (l.c. ante p. 105), [54], p. 444.

[‡] Sverdrup, Johnson & Fleming, (l.c. ante p. 113), [63], Chap. XIV.

ocean-waves to travel in groups in deep water at a speed of half the velocity of the individual waves. It was shown that when such a group of waves enters shallow water, the velocity of the group becomes sensibly equal to the velocity of the individual component waves, so that the resultant waves in the group advance as individual waves in their own right. The arrival of a group of such waves at a coastline in this way will be marked by a rapid increase in the size of the breakers until the full body of waves of about equal amplitude arrive, after which the surf will diminish and a comparative lull occur until the arrival of the next group of waves.

The standing-wave system induced by these waves and their reflections will exhibit beat-characteristics, wherein the amplitudes appear to be subject to a slow sinusoidal variation having a periodicity of its own. In the simplest case where two constituent wave-trains are responsible for the original wave-groups forming the seiche-beats, we may resolve the latter and identify its constituent standing-waves.

Thus, consider the superposition of two systems of standing waves whose vertical surface displacements in terms of (14)-(ii) are $\eta_1 = A_0 . \mathrm{Cos}\, q_1 x . \mathrm{Sin}\, p_1 t$ and $\eta_2 = A_0 . \mathrm{Cos}\, q_2 x . \mathrm{Sin}\, p_2 t$. For simplicity their amplitudes A_0 are taken the same and the epochs are discarded. When these systems are added, the resulting surface displacement is found to be

$$\eta_1 + \eta_2 = 2A_0 \Big[\mathrm{Cos}\,\tfrac{1}{2}(q_1+q_2)x . \mathrm{Cos}\,\tfrac{1}{2}(q_1-q_2)x . \mathrm{Sin}\,\tfrac{1}{2}(p_1+p_2)t . \mathrm{Cos}\,\tfrac{1}{2}(p_1-p_2)t$$

$$- \mathrm{Sin}\,\tfrac{1}{2}(q_1+q_2)x . \mathrm{Sin}\,\tfrac{1}{2}(q_1-q_2)x . \mathrm{Cos}\,\tfrac{1}{2}(p_1+p_2)t . \mathrm{Sin}\,\tfrac{1}{2}(p_1-p_2)t \Big]$$

If the periodic frequencies p_1 and p_2 are not very markedly different, we may overlook the small difference in the wavelengths by making $q_1 = q_2 = q$, with the result that

$$\eta_1 + \eta_2 = \{ 2A_0 \mathrm{Cos}\,\tfrac{1}{2}(p_1-p_2)t \} . \mathrm{Cos}\, qx . \mathrm{Sin}\,\tfrac{1}{2}(p_1+p_2)t \quad \text{———} (32)$$

Comparing this with equation (14)-(ii), we find that the amplitude of the resultant seiche,

$$A = 2A_0 \cdot \cos\left(\frac{p_1-p_2}{2}\right)t.$$

decays and grows sinusoidally at a low frequency ω, where

$$\omega = \frac{p_1-p_2}{2}$$

while the main standing waves appear to have a frequency

$$p = \frac{p_1+p_2}{2}$$

If ω and p are measured, the constituent periodicities can then readily be found from

$$\left.\begin{array}{ll} \text{(i)} & p_1 = p+\omega \\ \text{(ii)} & p_2 = p-\omega \end{array}\right\} \text{————————————} (33).$$

86. Graphical Charting of Wave-Propagation.

We come now to consider the graphical methods used by the author for examining the mechanism of seiches in the vicinity of the harbour in Table Bay. They developed really as bye-products of a method of integrating graphically the propagation of waves in different depths of water, based on the hydrodynamical equation for wave-velocity given by (1), (p. 107). It will be necessary to prefix our discussion on seiches with some general description of the latter method.

By the use of equations (1) and (8), the distances travelled by both long and short waves in different depths of water in a small interval of time (10 seconds) were calculated and plotted in a handy form, as in Fig. 100. The distance-scale adopted was 1 inch to 2400 feet, to accord with the linear scale of the contoured depth-chart of Table Bay, upon which the graphical integration was performed. The depth scale of Fig. 10 was made suitably open to permit of depths being read to an accuracy of ½ foot.

By adopting any arbitrary straight-line frontage to represent the crest of a wave at zero time (Fig. 101), the advance of the wave could be plotted on the contoured depth-chart by marking off with dividers the intercepts of distance appropriate to the depth (obtained from Fig. 100), at suitable intervals along the line of the wave-front. The second line, adjoining the initial, straight one in Fig. 101, thus represents the crest of the wave 10 seconds later: the third line, 10 seconds later again, and so on. Owing to the slow rate of progress of waves in shallow water the wave-front gradually becomes refracted and bent at the coastlines, and the wave-crest rapidly assumes the curvature appropriate to the topography of the sea-bed and the ultimate boundary of the coast.

The success of this method of charting wave-progression* depends upon the accuracy of plotting and the appropriate selection of the constant time-interval so that the distances travelled by the wave in that time do not involve too great a variation in the depth. It was found very necessary always to draw in the line of each wave-crest as it was completed, so that the successive intercepts of distance along the streamlines or normals would be truly perpendicular to the wave-front.

In Fig. 101, the initial wave-front was taken along the straight line joining Green Point on the mainland with the southern extremity of Robben Island. The numbers on the crest-lines represent the elapsed time since the wave left its original position, on the assumption that the wave is a long ground-swell

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* Unknown to the author at the time, (1943), it had been developed earlier by Irribarren Cavanilles ('Obras de Abrigo de los Puertos', Revista de Obras Publicas, Jan., 1941; Transl., Dock & Harbr. Authy., Oct., 1942, [100], p. 125), who has remained the great exponent of this graphical approach to harbour problems (cf. 'Protection des Ports', Report to Internatl. Navign. Congr., Lisbon, 1949, l.c. ante p. 126, [82]). The method has also been used extensively in the United States, especially during the last war; (cf. Burt & Saur, 'Hindcasting Technique Provides Statistical Wave Data', Civ. Engg., Dec., 1948, [101], pp. 47-49.).

travelling at the speed of equation (8) (p. 108). Since the maximum depth of water involved in the advance is 120 feet, at the mouth of the bay, our definition of a ground-swell (p. 117), applied to Fig. 27, means that Fig. 101 will represent all waves of periods of 20 seconds or more.

Fig. 101 shows that a long wave takes a little over 10 minutes to reach the coast from the time of passing through the entrance-channel on the west side of Table Bay. The assumed orientation of the wave-front at zero time is seen to lead to a crescent shape near the shore which accords well with the configuration of the coastline. Greater accuracy, however, is obtained by starting the integration from outside the bay, and Figs. 102 to 106 show the wave-alignments on this basis when the directions of approach are from the south-west, west and north-west.

Altogether, there is not a great deal of difference in the shape of the wave-fronts at the shoreline of the bay when the swell-directions outside the bay vary as much as 90° in this way. South-westerly ground-swells tend to make slightly oblique contact with the shore, with waves running northward (Fig. 102): westerly swells arrive simultaneously at all points along the coast (Fig. 103); while north-westerly swells impinge obliquely with a slight southerly set (Fig. 105). Figs. 104 and 106 show that the direction of the swells outside the bay have little effect upon their ultimate directions of entry via the north channel of the bay.

In Fig. 107 we give the successive wave-fronts at intervals of 15 seconds for waves of this period from the south-west, for direct comparison with the crests of the south-westerly swell which were photographed from the air on September 15th, 1943, (cf. Section 27, p. 78), and are depicted in Fig. 21. This comparison, we believe, is a fairly convincing demonstration of the reliability of the graphical method. Fig. 107 accords with equation (1) or the upper curve in Fig. 100, applicable to short waves: by contrast, Fig. 108 traces the lines of advance at 15 second intervals of long ground-swells, as derived from equation (8) or the lower curve of Fig. 100. On the whole, as might be expected from consulting Fig. 27, there is very little noticeable difference in these two expositions. In all the graphical work relating to seiches, the integration was, of course, made applicable to long waves or ground-swells.

87. Graphical Analysis of Seiches.

Although Section 9 (p. 34) and Fig. 6 make it clear that south-westerly swells have the highest frequency in the area of ocean immediately west of Cape Town, it is patent from Figs. 102 to 108 that not only do westerly swells admit more wave-energy to Table Bay, but their ultimate crescent shape accords best with the stable coastline of the bay. We have therefore adopted a westerly orientation of the swells from outside the bay in all the subsequent work to be described, in the sure knowledge that any loss of generality from this cause will be small (cf. p. 250).

Figs. 109 and 110, then trace the paths of ground-swells from the west, respectively through the west and the north entrance-channels of Table Bay. On the basis that incident waves are fully reflected from the shore-lines and harbour walls, (justification for which has been noted in Section 84) (p. 243), and that wave reflections are in accordance with the laws of reflection of light, (justified by observation), the returning waves have been inserted on the same diagrams and numbered according to the elapsed times in minutes from the time the incoming waves left their starting point.

Only first reflections have been included to avoid over-complication. Nevertheless, in the immediate area of the harbour there are seen to be two main systems of reflected waves in each case, one coming from the Milnerton Shore and the other from the Eastern Mole of the harbour. As affecting the water body in the neighbourhood of the harbour, there are therefore, taking into account the influence of the north channel, two sets of incident waves and four main sets of reflected waves.

Considering the effects of the entrance channels separately, it is clear that the incident waves will form standing waves with their reflections according to the principles enumerated in the earlier part of this chapter. The reflected waves near the harbour, which run through each other, will also form standing waves, so that in the corner of the bay adjacent the harbour there will be, in effect, three systems of standing waves. The resultant seiche will therefore comprise no less than six systems of major standing-waves together with any minor standing waves that may be formed from re-reflected waves (not taken into account). The complexity of the natural phenomenon is at once apparent. In spite of this, we can gain a very good idea of what is taking place by considering the standing waves individually and then collectively, for waves of a particular periodicity. A few specific cases, as examples of this analysis, are described in the next chapter.

CHAPTER XII.

TABLE BAY AS AN OSCILLATING BASIN.

> "This equalising power of averages, by destroying all such fluctuations as are irregular or accidental, frequently enables us to obtain evidence of fluctuations really regular, periodic in their recurrence, and so much smaller in their amount than the accidental ones, that, but for this mode of proceeding they never would have become apparent".
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> —— Sir John Herschel,
> Discourse on the Study of
> Natural Philosophy, (1851).

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88. Mathematical Harmonic Analysis of Seichograms.

In the absence of any electrical or mechanical apparatus for the harmonic analysis of the various seichograms and marigrams collected during the researches at Cape Town, the author was at first obliged to undertake the identification of periodicities by cumbersome mathematical methods*.

Briefly, the principle followed in separating out the wave-components in any particular time-record of water-level at a given place, was to select tide-heights at intervals equal to the periods of the suspected components. If such height measurements are taken over a long period of time, compared with the period of a component, and are summed, the effects of other components will average out if their periods are incommensuable with that of the selected component. The sum so taken will then give N times the tide-height of this one component, where N is the number of periods over which the summation extends. If the component being considered has a period of say 60 minutes, then by dividing the tide curve into 5 minute intervals and taking every 12th tide-height over N periods of 60 minutes, 12 independent summations will be obtained, which when plotted against their 5 minute intervals will give the harmonic curve of the component, magnified N times.

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*Schuster's Periodogram method is here described, as elaborated by Eagle ('Fourier's Theorem & Harmonic Analysis,(London),1925,[102]) and Steinmetz ('Engineering Mathematics',(New York),1917,[103]).

The next process is to break down this harmonic curve into its fundamental component and higher harmonics as a Fourier series. The trouble, of course, lies in the fact that the period of a component is not initially known and must be ascertained by trial and error. This means the taking of several sets of summations for different trial-periodicities, and the construction of a 'periodogram' from which components can be identified.

Calculations of this type were performed in 1944 in respect of three comparatively simple-looking seichogram-curves for stations 11 and 19, outside the Eastern Mole, on August 25, 1943, (Fig. 44), and for station 19 on September 20th, 1943, (Fig. 46).

Curve 11 (Fig. 44) was selected for the first calculation as it appeared to be the simplest. The periodogram, however, indicated the presence of at least three fundamental components with periods of 52½, 61.2 and 66½ minutes, giving the following harmonic series:

(a) $\tau = \underline{52.5}, \underline{26.3}, \underline{17.5}, 13.1, 10.5,$.... minutes.
0.48, 0.89, 0.27, 0.09, 0.03,... inches.
(b) $\tau = \underline{61.2}, \underline{30.6}, 20.4, 15.3, 12.2,$.... minutes.
0.56, 0.34, 0.10, 0.12, 0.03,.... inches.
(c) $\tau = \underline{66.4}, \underline{33.2}, \underline{22.1}, \underline{16.6}, 13.3,$.... minutes.
0.25, 0.84, 0.47, 0.28, 0.06,.... inches.

The most prominent periodicities in this particular seichogram appear to be of about 26 and 33 minutes, with the overtones of 52.5 and 61.2 minutes and a periodicity of 22 minutes ranking next in importance.

The harmonic analysis of the seichogram for station 19 (Fig. 44), (recorded at the same time as the other), suggested that while the above series were obviously close to being the principal components, there were others of still longer periods, notably 117, 105, 98, 95, 91, 88, 79, and 72 minutes, which appeared to assume importance when the periodogram range was extended, Fig. 111. Check calculations, made by compounding the principal components, succeeded in re-establishing the main shape of the seichogram-curve.

The tremendous labour involved in breaking down a single seichogram in this way, by purely mathematical processes, ruled out this method as too unwieldy and complicated for general use. A search was therefore instituted to discover some more convenient and rapid means of divination, and fortunately this brought to light Chrystal's method of 'Residuation'.

89. Harmonic Analysis by Residuation.*

Chrystal's method of Residuation depends upon a prior knowledge of the approximate periodicities of the component waves; if these are wholly unknown and cannot be inferred from mere scrutiny of an harmonic curve, recourse must still be had to the periodogram method for identifying probable constituents. In most cases, however, it is possible to distinguish one or more of the components and assess their approximate periodicity merely from visual inspection, in which case the Residuation process becomes applicable.

If it is known, for example, that one of the components of the harmonic curve is an 11 minute seiche, then the curve can be 'residuated with respect to' the 11 minute wave and a new curve obtained in which the 11 minute component is absent. The new curve may then be residuated with respect to any other suspected periodicity that may have been evident from the start or may have become apparent, and the process repeated until the

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* Chrystal, " Investigation of Seiches of Loch Earn by the Scottish Loch Survey" , Trans. Roy. Soc. Edinb., Vol. 45, Part II, 1906, [104], pp. 382-387. Cf. also Shaw (l.c. ante p. 39), [52], Vol. I, p. 275.

final residual curve is a straight line or the main sine-wave of the tide-curve.

The essential process by which the residuation is carried out consists in displacing the seichogram relative to itself by an amount equal to half the periodicity of the suspected component, and in constructing a new mean-curve between the displaced originals. Mathematically it can be shown that by so doing the component being considered is eliminated. By successive approximations the periodicities of the component harmonics can be exactly determined.

Figs. 102 (a) and (b) are typical of the residuation analyses made by the author and his staff. It was found convenient in practice to transcribe the seichogram-curve to be investigated on to tracing cloth, and, after the first residuation had been performed, to prepare a further separate tracing of the residual curve. Successive residuations were then conducted alternately from one sheet to the other, by superimposing, displacing and tracing, as will be evident from the two sheets of Fig. 102.

Table IV gives the results of analyses by Residuation performed on selected seichograms from Figs. 42 to 58, grouped according to the location of the recording station to which they refer.

In the analysis work done at Cape Town residuation was only performed to the first approximation, and for that reason some personal factor is inherent in the results quoted. It was found that two independent investigators did not always arrive at the same result when analysing one particular record, although on the whole the differences were not of a serious nature. Several test cases are reflected in Table IV, as shown by the brackets. In most cases where disparities occur it will be found

Table IV: Apparent Periodicities of Range Oscillations (from Residuation).

General Location	Recorder Station	Fig. No.	Date of Record.	Apparent Periodicities (Mins)	Analyst
Outside Eastern Mole near Shore.	15	47	Oct. 4/43	—;—;—;25.7;—;—;11.4;—;—;5.7;4.5;3.8;2.8;2.2;—;—;—;—;—;—;—;—;	Wilson
	19	47	" "	—;—;—;25.7;—;—;11.4;8.6;—;5.7;4.5;3.8;2.8;2.2;—;—;—;—;—;—;—;—;	Wilson
	19	49	Nov. 6/44	—;51;—;25.7;—;—;11.5;—;6.9;—;4.9;4.3;2.8;2.0;—;—;—;—;0.75;—;—;0.25;	Joosting
	19	49	" "	58;—;—;29.0;—;—;11.1;—;—;5.6;4.3;—;—;2.2;—;—;1.06;—;0.71;0.62;0.49;—;	Wilson
	19	49	" "	—;—;—;—;—;—;10.2;—;—;5.7;4.2;—;—;2.3;—;1.52;1.10;—;—;—;—;—;	de Boer
	19	50	Nov. 8/44	—;—;—;—;18.6;—;10.9;—;7.4;5.5;—;3.5;—;2.1;—;—;1.06;—;—;—;—;—;	Wilson
	19	52	Aug. 6/46	62;—;—;23.4;—;14.0;—;8.8; ;5.4; ;3.4;2.8; ;1.74;1.54;1.09; ;0.70; ;0.41;0.33;	Joosting
	19	52	" "	—;—;—;—;—;14.5;11.0;—;—;5.5;—;3.8;2.5;—;—;—;1.10;—;—;—;—;0.36;	Cowan
	19	53	Aug.23/46	62;—;—;22.7;—;13.6;—;9.2;—;5.6;—;—;3.0;2.5;1.50;1.33;1.07;—;0.76;—;0.41;—;	Joosting
	19	53	" "	—;—;—;26.0;—;14.0;—;9.1;—;5.5;—;—;2.5;—;—;1.40;—;0.90;—;—;0.45;—;	Cowan
Entrance of Duncan Basin	11		Aug. 1/44	—;—;—;—;—;16.0;—;—;—;5.6;4.2;—;2.7;2.0;1.90;—;1.00;—;—;—;0.51;—;	de Boer
	11		" "	—;—;—;—;21.0;—;—;—;—;5.4;4.3;3.9;—;2.1;1.97;—;1.02;0.96;—;—;0.53;—;	Joosting
	11		Aug. 3/44	—;—;38;—;19.0;—;—;9.5;—;5.3;4.9;—;2.5;2.3;—;1.25;1.00;—;—;0.60;0.50;—;	de Boer
	11		" "	—;—;38;—;19.0;—;—;9.5;—;5.5;4.8;—;2.5;2.3;—;1.26;1.02;—;—;0.56;0.50;—;	Joosting
	11	48	Oct. 1/44	—;—;43;29.0;21.3;17.0;—;—;6.8;—;4.3;—;—;2.0;—;1.35;—;—;0.68;—;—;0.25;	Joosting
	11		June21/45	—;—;—;—;19.0;—;—;—;—;5.6;—;—; ;2.3;1.87;—;—;0.94;0.67;—;0.49;—;	Joosting
	11		July 7/45	—;—;—;—;—;14.0;—;—;7.0;5.6;—;—;2.6;—;1.76;—;1.00;—;0.69;0.54;—;—;	Joosting
	11		July31/45	—;—;—;—;21.0;—;—;—;—;5.9;—;3.5;—;—;1.87;—;1.05;—;0.71;—;0.50;—;	Joosting
Breakwater Bight ex Vict. Basn.	1	48	Oct. 1/44	62;—;—;31.0;19.2;12.1;10.1;—;—;—;4.1;—;—;2.2;—;—;—;—;—;—;—;—;	Joosting
	1	49	Nov. 6/44	—;51;—;—;20.3;—;—;9.8;—;5.5;—;—;2.8;—;1.60;—;—;—;—;—;—;—;	Joosting
	1	50	Nov. 8/44	—;—;—;—;21.0;—;11.0;—;—;5.8;—;3.5;2.9;—;1.68;—;—;—;—;—;—;—;	Wilson
Inside Victoria Basin.	4	48	Oct. 1/44	62;—;—;31.0;18.6;—;11.5;8.7;7.8;—;4.2;—;2.8;—;—;—;—;—;—;—;—;—;	Joosting
	4	49	Nov. 6/44	—;51;—;22.5;—;—;11.2;9.5;—;5.5;4.1;—;2.8;—;—;1.39;—;—;—;—;—;—;	Joosting
	8		June20/45	—;—;—;—;—;—;10.8;—;—;5.4;—;3.1;2.8;2.3;1.91;—;1.10;0.87;—;—;—;—;	Joosting
Inside Duncan Basin.	12		Aug.30/44	—;—;—;28.0;—;14.0;—;—;—;5.6;4.7;3.8;—;2.2;1.90;1.30;1.00;—;—;—;0.50;—;	de Boer
	12		" "	—;—;—;28.0;—;14.0;—;—;—;5.5;4.8;3.4;—;2.2;1.89;1.42;1.00;0.91;—;—;0.50;—;	Joosting
	12	49	Nov. 6/44	—;52;—;26.0;18.0;—;11.2;—;6.3;—;4.3;—;—;2.0;—;1.53;—;0.90;—;—;0.45;0.25;	Joosting
	12	50	Nov. 8/44	—;—;—;27.5;—;13.7;—;—;—;5.5;4.1;—;—;2.1;1.68;1.22;—;—;0.71;—;—;—;	Wilson
	12	50	" "	57;—;—;28.3;—;14.1;—;—;6.5;—;4.3;—;—;2.1;—;1.41;1.15;—;0.66;—;—;0.25;	Joosting
	12/C	52	Aug. 6/46	—;—;—;—;—;14.0;—;—;—;5.9;4.0;—;—;—;—;—;—;0.95;—;—;—;—;	Cowan
	12/C	53	Aug.23/46	—;—;—;—;—;—;—;—;—;—;4.0;—;—;—;—;—;1.05;0.80;—;—;—;—;	Cowan
	A	52	Aug. 6/46	—;—;—;—;17.0;—;—;—;—;5.4;—;—;—;2.1;—;1.57;—;—;—;—;—;—;	Cowan
	A	53	Aug.23/46	—;—;—;—;—;13.0;—;—;—;5.5;—;—;—;—;—;1.44;1.00;—;—;—;—;—;	Cowan
	E/F	42	Aug.15/45	—;—;—;—;—;16.0;—;—;—;5.5;—;3.8;2.6;—;—;1.50;—;0.90;—;—;—;—;	Cowan
	E/F		Nov.17/45	—;—;—;—;—;—;11.0;—;—;5.6;—;—;2.6;—;1.91;1.50;—;—;0.76;—;—;—;	Cowan
	E/F		Dec. 7/45	—;—;—;—;—;—;11.0;—;—;5.6;—;3.5;—;—;1.75;1.55;—;0.93;—;—;—;—;	Cowan
	14	48	Oct. 1/44	—;—;—;29.0;18.6;17.0;—;9.8;6.6;—;—;—;—;—;1.77;—;—;—;—;—;—;—;	Joosting
	16	48	Oct. 1/44	—;—;—;29.0;19.1;12.7;—;—;—;5.0;—;—;—;—;1.66;—;—;0.89;—;—;0.43;—;	Joosting
	16	49	Nov. 6/44	—;51;—;20.4;17.4;12.2;—;—;—;—;4.6;3.8;—;—;1.86;1.29;—;—;0.68;—;—;0.25;	Joosting
	18	48	Oct. 1/44	—;—;—;29.0;19.1;12.2;—;—;—;—;4.7;—;—;—;1.66;—;—;—;—;—;0.43;—;	Joosting
Incomplete Residuations:					
Inside Duncan Basin.	E/F	56	Aug.12/44	71;55;—;32.0;21.0;—;—;—;	de Boer
	E/F		Sept10/44	58;—;—;33.0;16.4;—;—;—;	Wilson
	E/F	58	Aprl 9/46	61;—;48;34.0;28.6;—;—;—; 25.2	Wilson

that the mean of two periodicities in sequence, found by one investigator and not by another, will agree with an intermediate periodicity found by the other.

The repeated recurrence of certain periodicities in the residuations, undertaken on widely separated occasions, seems, nevertheless, to prove their reality statistically, and to establish the general reliability of the Residuation process: but of this more will be said when we come to compare all the assembled data of field observations, model experiments and theoretical prognoses.

90. The South Atlantic as an Oscillating Basin.

In Section 12 (p. 37) and Fig. 7 we drew attention to the fact that the submarine mid-Atlantic ridge, running almost concentrically with the west coast of South Africa, together with the submarine spur, in effect, joining the west coast with the Tristran da Cunha group of islands, gave the ocean immediately west of Cape Town the configuration of a basin, the oscillating properties of which might have a bearing on our problem.

It would appear from Fig. 7 that we could justifiably consider the ocean west of Cape Town both as a rectangular basin of length $L =$ 1700 miles, with parabolic bottom of maximum depth $d_0 =$ 2700 fathoms, and as a triangular canal, (with the apex on the west coast of Africa at the junction of the submarine spur with the mainland), of length $L =$ 1000 miles and uniform depth $d =$ 2250 fathoms.

Any disturbance of the water mass of the ocean would very likely set up seiches in these huge basins, in which case the oscillations could be expected to have periods as given by equation (20), for the larger rectangular basin, and equation (31) for the smaller triangular one.

For the dimensions given above, these periodicities are computed to be:

Rectangular Basin:

$\tau =$ 460, 265, 188, 145, 119, 100, 87, 77, 68, 62, 57, 52, 48, 45, 43, ... minutes

Triangular Basin:

$\tau =$ 350, 152, 97, 71, 56, 46, 39, 34, 30, 27, ... minutes.

Collectively, therefore, periodicities in the following sequence might be found anywhere along the west coast of southern Africa:

$\tau =$ 460, 350, 265, 188, 152, 145, 119, 100, 97, 87, 77, 71, 68, 62, 57-56, 52, 48-46, 45-43, 39, 34, 30-27, ... minutes. ________ (34)

These figures are at once arresting in view of their extraordinary congruency with the results of the harmonic analysis given in Section 88, (p. 254), and Fig. 111. To make the comparison complete, we give below the main periodicities as found by harmonic analysis in the No. 19 seichogram of Fig. 44, (extracted from Fig. 111), and the natural periods for the oceanic oscillating basins, as computed from equations (20) and (31):

Table V: Computed and Recorded Periods for South Atlantic Ocean.

Periods in Seichogram No. 19 (Fig. 44)	117	105	98-95	91-87	79	72	66	61	57	52	48
Natural Periods of Ocean Basins	119	100	97	87	77	71	68	62	57-56	52	48-46
Periods in Seichogram No. 19 (Fig. 44)	43	39	35	30-25	21	.... minutes.					
Natural Periods of Ocean Basins	45-43	39	34	30-27		.... minutes.					

The remarkably consistent agreements between these figures surely transcends any possibility of their being the result of mere random chance. It may reasonably be inferred that the water mass of the South Atlantic ocean does in fact oscillate in the two submarine basins we have envisaged, with the fundamental periods of 460 and 350 minutes and all their numerous higher harmonics. Were the periodogram analysis of the seiche records for Table Bay extended sufficiently, we might expect to come upon evidence of the remaining periodicities reflected in (34), (p. 259). Fig. 111, at any rate, appears to accord with the theoretical requirement that the lower modes of oscillation become more widely separated in the periodogram.

The longer periods found by residuation in other seichograms (Table IV) also fit perfectly into the above pattern. We are led to see from this how the meteorological disturbances of the South Atlantic, and especially the powerful barometric oscillations, that we have described in earlier chapters, can influence the whole water body of the ocean in its quasi-oscillating basins: how the higher harmonics[*] of these vast movements can find response in particular bays and irregularities of the coastline in the form of local seiches of small, sometimes minute amplitude, perceptible only to a sensitive recording instrument. We thus have an explanation for particular long periodicities found in the seiches of Table Bay, although there remains to examine why it is that certain of these, especially the periods of 62-51, 33-25, 21-18 minutes attain such prominency. It is not difficult to foresee that of its own accord Table Bay must be 'tuned' to these frequencies, and that it takes up the work of stimulating seiches in its own oscillating area when the rapid convergence of the series of oceanic seiches, both in period and amplitude, causes a fading out of the stimulus from farther afield.

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[*] The implications of this finding are that both odd and even harmonics are excited by the disturbing agencies as free oscillations of the ocean basins.

91. The Natural Periods of Oscillation of Table Bay.

The analysis of the last chapter permits of our investigating the possible modes of oscillation of the water-body in Table Bay from several different standpoints which approximate to the conditions.

1°. We may, for instance, regard the bay as approximating to an enclosed rectangular basin of parabolic bed in the direction of its major axis. As such, equation (20), (p. 238), would apply, and the dimensions would be $L = 46,800$ feet and $d_0 = 90$-95 feet, according to the state of the tide (p.35).

2°. We might also regard it as the half of an enclosed rectangular basin with parabolic bed in the direction of its breadth or minor axis. The second half of the basin in this case would be imaginary and we should be restricted, in applying equation (20), to adopting only those modes of oscillation which gave a node at the centre of the imaginary basin; that is, at the west entrance-channel of the bay. In these circumstances the length of the basin would be $L = 2 \times 31,200$ feet, and the depth $d_0 =$ 120-125 feet, while m would be limited to the odd values 1,3,5, ...

3°. A third approximation would be to regard Table Bay as a broad, rectangular canal with a plane botton sloping down to its mouth, (the west channel), open to the sea. This case is treated in equation (30), (p. 245), and the appropriate dimensions would be $L = 31,200$ feet and $d_0 = 120$-125 ft.

4°. If we consider the bay as a fully enclosed circular basin of paraboloidal bed,-equations (24) are applicable and the dimensions will be $D = 39,000$ ft. and $d_0 = 90$-95 ft. The diameter has here been taken as the mean of the major and minor axes of the bay, respectively 46,800 and 31,200 ft. in length.

5°. More accurately, Table Bay may be regarded as the full half, about a diameter in the west channel, of an enclosed circular basin of paraboloidal bed, the other half of which is imaginary. Equations (24) apply again, in which the diameter will now be $D = 49,500$ ft., (the curvature of the Milnerton-Blaauwberg Strand coastline) and the maximum depth $d_0 = 120\text{-}125$ feet. As in case 2°, we shall be obliged in this instance to consider only the odd modes of oscillation such as will yield nodes in the entrance channel.

6°. Next, we may assume Table Bay to approximate to a fully enclosed elliptical basin of uniform depth, the dimensions of which are $L = 46,800$ and $B = 31,200$ ft., making B/L exactly 2/3, while $d = 70\text{-}75$ ft. on the average, according to the tide condition. Only one mode, the fundamental, can be calculated for these circumstances from equation (27).

7°. More appropriate to the bottom shape of Table Bay is equation (28) which applies to an enclosed elliptic basin of ellipsoidal bed for the particular dimensional ratio $B/L = 2/3$. As for 6°, $L = 46,800$ ft., while $d_0 = 90\text{-}95$ ft.

8°. Yet another approximation to the conditions may be made by treating Table Bay as a rectangular canal of uniform depth, closed at one end and open to the sea at the other. Taking the bay in the direction of its length with the mouth of the supposed canal at the north entrance-channel, we have $L = 46,800$ ft. and $d = 61\text{-}66$ ft. on the average, allowing for tidal variations, and the successive modes of oscillation will then be given by equation (29).

9°. Finally, the bay may be treated in the same way as for 8° but in the direction of its breadth, the mouth of the hypothetical canal now lying in the west entrance-channel. Equation (29) will apply again with the dimensions in this case $L = 31,000$ ft. and $d = 81\text{-}86$ ft.

The results of feeding these data to the respective

Table VI: Natural Periods of Seiches in Table Bay from Approximate Hydrodynamical Theory.

Case No.	Analogy			Equation No. Applicable	Symbol Values			State of Tide	Calculated Periods of Natural Modes of Oscillation (Minutes).
	Shape of Basin	Type of Bed	Axial Direction		L or D	d or d_o	m or s		
1°	Enclosed Rectangular	Parabolic *	Length of Bay	20	46800	90	1,2,3,...	Low	— ; — ;32.2;18.6;13.1; — ;10.2; 8.3; 7.0; 6.1; 5.4; 4.8; 4.3; 4.0; ...; ...; ...;
						95		High	— ; — ;31.3;18.1;12.7; — ; 9.9; 8.1; 6.8; 5.9; 5.3; 4.7; 4.2; 3.9; ...; ...; ;
2°	Half of Enclosed Rectangular	Parabolic	Breadth of Bay	20	62400	120	1,3,5,...	Low	— ;37.2; — ; — ;15.2; — ; 9.6; — ; 7.0; — ; 5.5; 4.6; — ; 3.9; ...; ...; ;
						125		High	— ;36.4; — ; — ;14.9; — ; 9.4; — ; 6.9; — ; 5.4; 4.5; — ; 3.8; ...; ...; ;
3°	Open Rectangular	Inclined Plane	Breadth of Bay	30	31200	120		Low	— ;37.2;....;....; ; ; ; ; ; ; ; ; ; ; ; ; ;
						125		High	— ;36.4;....;....; ; ; ; ; ; ; ; ; ; ; ; ; ;
4°	Enclosed Circular	Paraboloidal		24	39000	90		Low	— ; — ;26.8; — ;13.4; — ;10.1; 7.8; — ; 6.5; 5.5; 4.8; 4.2; 3.8; 3.5; 3.2; 2.9; ...
						95		High	— ; — ;26.1; — ;13.0; — ; 9.8; 7.5; — ; 6.3; 5.3; 4.7; 4.1; 3.7; 3.4; 3.1; 2.8; ...
5°	Half of Enclosed Circular	Paraboloidal	Breadth of Bay	24	49500	120		Low	— ; — ;29.5; — ; — ;11.1; — ; — ; 7.2; — ; 5.3; ; 4.2; — ; 3.5; — ; 2.9; ...
						125		High	— ; — ;29.0; — ; — ;10.9; — ; — ; 7.0; — ; 5.2; — ; 4.1; — ; 3.4; — ; 2.8; ...
6°	Enclosed Elliptic	Level Plane	Length of Bay	27	46800	70		Low	— ; — ;27.6;....; ; ; ; ; ; ; ; ; ; ; ; ; ;
						75		High	— ; — ;26.7;....; ; ; ; ; ; ; ; ; ; ; ; ; ;
7°	Enclosed Elliptic	Ellipsoidal	Length of Bay	28	46800	90		Low	— ; — ;32.2;21.0;15.9;11.9;10.4;....; ; ; ; ; ; ; ; ; ;
						95		High	— ; — ;31.3;20.4;15.4;11.6;10.2;....; ; ; ; ; ; ; ; ; ;
8°	Open Rectangular	Level Plane	Length of Bay	29	46800	61	1,3,5,...	Low	70.4; — ; — ;23.5;14.1; — ;10.1; 7.8; — ; 6.4; 5.4; 4.7; 4.1; 3.7; — ; 3.4; ...; ...
						66		High	66.5; — ; — ;22.6;13.5; — ; 9.7; 7.5; — ; 6.1; 5.2; 4.5; 4.0; 3.6; — ; 3.2; ...; ...
9°	Open Rectangular	Level Plane	Breadth of Bay	29	31200	81	1,3,5,...	Low	— ;41.0; — ; — ;13.7; — ; — ; 8.2; — ; — ; 5.9; 4.6; — ; 3.7; — ; 3.2; 2.7; ...
						86		High	— ;39.8; — ; — ;13.3; — ; — ; 7.9; — ; — ; 5.7; 4.4; — ; 3.6; — ; 3.1; 2.7; ...

* On the basis that the bed is part of a quartic curve, it can be shown that the periodicities, based on equations (22) and (23) and observational values of τ_1 and τ_2 (respectively 29 and 19 minutes - cf. Table IV), are almost identical with this Case; e.g.; 29, 19, 13.6, 10.5, 8.5, 7.1, 6.1, 5.4, 4.6, 4.3, ...

equations in the 9 cases are presented in Table VI , (p. 263).

In Table VI the calculation of periodicities from the various equations has been continued until their convergence and high harmonicity indicate that extensions of the series would have no further reliability or meaning. Much the same grouping has been resorted to as was adopted in Table IV, with which we now invite comparison.

While it must be remembered that the periodicities recorded in Table IV pertain more particularly to seiches in the harbour area where the effects of the breakwater and the docks vitally influence the higher frequencies, there are nevertheless, in spite of this, many striking resemblances between the observed and calculated periods. Nearly all the observed periodicities in the lower modes found at different times in Table IV can now be explained on the basis that the water in the bay was oscillating (for short intervals only perhaps), in one or other of the analogies set forth in Table VI (cf. p.138). It seems, in fact, probable that the true oscillations of the bay are very much a composite of all the nine cases we have envisaged.

One of the most astonishing things is that, when the bay is considered to perform according to the analogies 1° to 9°, so many of the natural frequencies for the different cases accord with each other. Thus, as between the natural periods of 1°, 4° and 7°, there are no very serious differences except that certain modes of oscillation are entirely absent in particular instances. Nearly all the other cases also fall into line by reinforcing each other in certain frequencies. The particular periodicities most uniformly represented are in the categories 32-26, 16-12, 11-10, 5.8-5.3 minutes, and these are some of those most commonly found in the marigrams and seichograms for the harbour (Table IV).

Seiches of 17-23, 51-55, 57-66 minutes are, however, also of considerable prominence in the records for Table Bay, and while the first of these three ranges is covered by Cases 1°, 7° and 8°, the second and third are very inadequately represented by 8° alone. The persistence of 17-23 minute seiches in Table Bay suggests, in the light of Cases 1°, 7° and 8°, that these oscillations are binodal ones in the longitudinal direction, along the long axis of the bay. To a large extent, therefore, the bay must function as a closed basin. The absence of the other ranges, 51-55 and 57-66 minutes, in the natural periods for the bay, as given by Table VI, on the other hand, does not necessarily mean that the results are invalidated, for, as we have seen, these particular low frequencies are forced oscillations from the wider oceanic basins outside the bay. There must, nevertheless, be some features of Table Bay which permit of a degree of resonance at these frequencies and the implications of this must therefore be subjected to the more exacting scrutiny of the graphical methods referred to in Section 87 (p. 251).

92. Fundamental Oscillations for Table Bay from Graphical Analysis.

From Equation (18) (p. 237) we noted that the fundamental oscillation for a closed basin was equivalent to a standing wave of wave-length twice the length of the basin: in contrast, equation (29), giving the fundamental mode for an open basin ($s = 1$), indicates that the equivalent standing wave has a wave-length four times the length of the basin. If, therefore, it takes a ground-swell t minutes to travel from the entrance channel of the bay to the opposite shore where it is reflected, the period of wave which will produce, with its reflection, a standing wave having a node in the entrance-channel, will be $\tau = 4t$, and such a ground-swell will produce the fundamental seiche for the bay.

From Fig. 109 we see that an incoming westerly ground-swell reaches the west-channel of Table Bay at $t = 4\frac{1}{2}$ to 5 minutes after it left its position at zero time. It reaches the Milnerton-Blaauwberg coast at $t = 15$ minutes. The fundamental seiche for the bay via the west-channel will therefore be $\tau = 4(15-4\frac{3}{4})$ or 41 minutes, which is exactly the result given by Case 9° in Table VI.

The same westerly ground-swell crosses the threshold of the north-channel of the bay (Fig. 110) at $t = 8\frac{1}{2}$ minutes and finally reaches the farthest extremity of the bay at the root of the Eastern Mole at $t = 26$ minutes. The period of the fundamental seiche via the north-channel will therefore be $\tau = 4(26-8\frac{1}{2})$ or 70 minutes, which again agrees exactly with the theoretical prediction of Case 8° (Table VI). Considering the fact that the wave-propagations traced graphically in Figs. 109 and 110 are referred to LWOST, the success of the approximate theory in Cases 8° and 9° is quite remarkable.

The position, however, will be different when the ground-swell approaches the bay from the south-west direction, for then the tendency will be for the node of the fundamental oscillation to form outside the west-channel of the bay, more or less at right angles to the promontory of land between Sea Point and Green Point, (Fig. 102). From this position, Fig. 108 shows, it takes a ground-swell from $12\frac{1}{2}$ to $14\frac{1}{2}$ minutes to reach the opposite coast at Blaauwberg strand, so that the fundamental period of oscillation in these circumstances will be from 50 to 58 minutes at low tide.

We may notice from Fig. 7 that the longitudinal axis of the rectangular-shaped South Atlantic basin lies along a direction slightly south of south-west while that of the triangular basin is slightly west of south, so that any forced oscillations impressed upon Table Bay, arising from the free oscillations of the outer ocean, have the correct direction to correspond with a critical mode of oscillation such as envisaged above. In fact the general direction is so nearly parallel to the part of the Cape Peninsula between Mouille Point and the Karbonkelberg, that even lower modes of oscillation are possible, the nodes of which could lie anywhere between these points. We could on this basis probably explain the resonance of seiches in the frequency band from say, 80 to 40 minutes, all promoted by oceanic oscillations.

In the range of periodicities between 78 and 66 minutes, however, Table Bay will respond naturally by developing a fundamental seiche via the north-channel, on account of the varying time taken, (from 16½ to 19½ minutes), for ground-swells to reach the head of the bay from the wide threshold of that channel.

But it need not be supposed that the prominent periodicities of 62, 57, and 51 minutes encountered in Table Bay are necessarily always dependent upon the oscillations of the ocean as a whole, for, as we have seen, they are to a large extent forced by the overhead barometric oscillations whose periodicities often happen to accord closely with these particular values (cf. pp. 144, 203). The direction of approach of the overhead disturbances, moreover, would affect the issue, and if north-west were the prevailing direction, as is usually found, Fig. 105 shows that a node off the southern point of Robben Island, parallel to the coast at the last point of arrival of the forced ground-swell in the bay via the west-channel, would accord with a periodicity of about 58 minutes. With a wide range of latitude here and allowances for tide-height, it is easy to see how oscillations of 62, 57 and 51 minutes could arise, essentially dependent upon the direction of approach.

93. The Shape and Form of Seiches in Table Bay.

We may extend the exploration of seiches by graphical means to the higher modes of oscillation by the simple expedient of following the progress into the bay, and out again, after reflection, of a wave of any desired periodicity.

In Fig. 113, (which is a varient of Fig. 109), for example, a ground-swell of 22 minutes periodicity, entering the bay through the west-channel, is assumed to have just reached the shore, where, with its reflection from the Milnerton shore, it forms the antinode of a standing wave. To find the nodes and ventral loops of this standing wave, we have merely to add together the component incoming wave and its reflection.

With the crest of the incoming wave at the shore at $t = 15$ minutes, its succeeding trough, which trails it by 11 minutes, must be at the frontal line for $t = 4$ minutes. The antecedent trough of the reflected wave, on the other hand, preceding the crest by 11 minutes, must simultaneously be at $t = 26$ minutes on the dash-dot frontal line of the reflections (Fig. 113). These trough lines at $t = 4$ and $t = 26$ happen to lie very close together in Fig. 113, and the true trough of the standing wave can very simply be located by drawing a mean line between the two fronts, as shown.

In between the crest and the trough of the incoming, and of the outgoing, wave the nodes will be found at $t = 9\frac{1}{2}$ and $t = 20\frac{1}{2}$ minutes. The node of the standing wave, therefore, will lie midway between the frontal lines for these times, and will in fact intersect incident and reflected wave-fronts wherever their time difference is 11 minutes or half of the wave period. The node of the standing wave, as located in this way, is shown in Fig. 113.

The same principle applies in locating any particular height contour of the resultant standing wave, on the assumption that the amplitudes of the incoming and reflected waves are equal. For instance, if we drew a line intersecting the full and dash-dot frontal lines wherever the time difference was 9 minutes, as shown by the dash line to the east of, and parallel with, the node in Fig. 113, we should arrive at a contour on the rising sine curve of the standing wave at a time distance from the node of 1 minute or 1/22 x 360°. Alternately, if we wished specifically to find the 45° contour between the node and the crest, that is, $2\frac{3}{4}$ minutes removed from either node or antinode of the standing wave, we should have to look for incident and reflected fronts whose time difference was exactly $5\frac{1}{2}$ minutes or one quarter of the period. By this means the general features of a standing wave system can rapidly be inserted on such a chart as Figs. 109 or 110.

Near the harbour, as we pointed out in Section 87, (p. 252), there are in general six systems of standing waves arising from waves entering Table Bay via its two channels. It will be instructive to examine how these systems react on each other in the particular case say of an 11 minutes seiche, which is such a persistent feature of marigrams and seichograms for the harbour.

The purple set of contours of Fig. 114 represents the standing wave set up by an 11-minute incident wave from the west-channel and its reflection off the Paarden Eiland shore, similar in general characteristics to the 22-minute standing-wave we have just considered. Whereas the node of the latter ran parallel to the shore from the end of the breakwater (Fig. 113), the node of the 11-minute standing wave runs parallel to the coast from the middle distance between the breakwater and the shore. The antinode, opposing that at the shore, now lies in line with the breakwater. A further node and antinode, to seaward of the harbour, are also shown in Fig. 114. The contours divide the standing-wave into $\frac{1}{2}$-minute intervals, and their height-values in relation to an assumed amplitude of unity at the antinodes are indicated by annexed figures.

In the same way the red contours represent the standing wave formed by the 11-minute incident wave and its reflection off the harbour walls. Three nodes are involved in this case, the outer one of which need not concern us, as it derives from the reflections on the seaward side of the breakwater and is outside the area of particular interest.

The reflected waves from the Paarden Eiland shore and from the harbour walls pass through each other to form the third standing wave system, shown in green in Fig. 114, again with two nodes crossing each other almost at right angles.

The three principal standing-wave systems evolved from Fig. 110 for incident waves entering the bay via the north-channel are illustrated by corresponding colours in Fig. 115.

Each group of three standing waves (Figs. 114 and 115) forms a seiche. The standing waves are synchronous and form co-incidental antinodes at the root of the Eastern Mole. Their resultant seiche is therefore simply found by adding them together. We should note here that by taking the three standing-waves together, we are really adding the incident and reflected waves twice over, and therefore to get the effect of the incident and two reflected waves once only, we should halve our summations. We avoid this necessity however by regarding the amplitude of each of the three standing waves as unity. This in effect has already performed the halving, because, if the incident and reflected waves are all considered to have unit amplitude from the start, the amplitude of each standing wave should really be 2, (cf.p.235).

The summations have been performed in Fig. 116. The west-channel and north-channel seiches are separately given in red and green, and the maximum amplitude of each, at their anti-nodes at the root of the Eastern Mole, is 3. These two seiches are co-existent, but not necessarily in phase, since the phase will depend on the relative times at which the incident waves, via the two channels, reach the root of the Eastern Mole. Here it is necessary to digress somewhat in order to consider this question of phases.

The relative times of arrival at the root of the Eastern Mole of west-channel and north-channel waves, for different initial directions of approach of swell in the outer ocean, are recorded below in Table VII:

Table VII: Phase Differences between West and North Channel Seiches.

Swell Direction.	Time of Arrival of Wave Crest at Root of Eastern Mole. (Mins).		Phase Difference (Mins).
	West Channel	North Channel	
North-west	19	$22\frac{1}{4}$	$3\frac{1}{4}$
West	15	26	9
South-west	$13\frac{1}{2}$	$30\frac{1}{2}$	17

These figures were derived from the graphical work described in Section 86 (p. 248) and are probably fairly accurate. It is clear then that the phase difference can be anything from 3 to 17 minutes according to the possible directions of approach of swell converging on Table Bay. For any periodicity up to 17 minutes there must therefore be at least one swell direction which will make the phase-difference a complete multiple of the periodicity, in which case perfect synchronism of the west and north-channel component seiches is possible.

In the particular case of 11-minute waves entering the bay it will be obvious from Table VII that when their direction of approach is slightly south of west, the north and west-channel seiches will be completely additive, and the final resultant seiche will therefore take the form of the purple system of contours in Fig. 116, giving an amplitude at the antinodes 6 times that of the waves entering the bay.

Although this result must be accepted with some reserve because wave-heights are influenced by the depth of water over shoaling ground, nevertheless it serves to illustrate the general mechanism of seiches and the manner in which they become exaggerated in amplitude.

Of particular significance is the fact that the resultant 11 minute seiche is found to be almost the exact uninodal seiche for the quasi-oscillating basin between the breakwater and the shore. If this circumstance had been fully taken into account, by recording reflections of reflections, we should have arrived at a resultant seiche of still greater amplitude. We have, anyway, a very satisfying picture of the mysterious phenomenon which so persistently affects the Alfred and Victoria Basins. It accords, moreover, with the seichogram findings discussed in Section 48 (pp. 140-141), where it was shown that there was definite evidence of an 11-minute uninodal seiche between breakwater and shore, outside the harbour.

Although, for the purposes of demonstrating the constitution of seiches near the harbour, we have set out in full almost purely graphical methods of arriving at the seiche resultant, we could more directly have added the wave-heights of the incident and reflected swells at selected points on the reticulation or co-ordinate system of Figs. 109 and 110, to give the same result.

Numerous similar graphical analyses of seiches were undertaken by the author and his staff at Cape Town, particularly of such periodicities as $5\frac{1}{2}$, $4\frac{1}{2}$, $3\frac{1}{2}$, $2\frac{3}{4}$, $2\frac{1}{4}$ minutes. The voluminous nature of this work precludes its presentation here, but the nature of the seiches is in all cases similar to the example we have taken. With the higher frequencies, of course, there are more nodal lines taking off at right angles from the Eastern Mole, and these tend to curve round on each other after the fashion of the $2\frac{3}{4}$ minute seiche whose approximate configuration is illustrated in Fig. 117. As might be expected, a $5\frac{1}{2}$ minute seiche is exactly binodal for the breakwater-shore oscillating system: and many of the other periodicities discovered in Table IV may be recognised as higher harmonics of the 11-minute fundamental seiche in this corner of the bay.

94. Seiches in Table Bay from Model Experiments.

We propose now to anticipate the description of the model researches by giving here some experimental results which are pertinent to the present topic.

Figs. 118, 119 and 120 all show the general lay-out of the model harbour and bay as constructed in the Range Laboratory at Cape Town. The orientation will be clear from a comparison of these diagrams with, say, Fig. 109.

The sea-bed in the model is correctly moulded to the shape of the contours over the contoured area of Figs. 118 to 120. Paddles A, B, C, D and E, F, G, in the locations shown, simulate the effects of swells entering the bay via the west and north channels. The paddle wells or bays permit of the slewing of the paddles to an extent sufficient to cater for south-west, west and north-west swell directions in the outer ocean. Figs.

118 to 120 show specifically the degree to which the waves actually propagated by the wave paddles, as found by experiment (to be later described), agree with the graphically integrated wave-fronts for westerly swells (Fig. 118) and south-westerly swells (Fig. 119) through the west channel, and for all swells (Fig. 120) through the north channel.

On the whole, it will be seen that the wave-paddles succeed in producing the expected directional approach of swells to the head of the bay. The agreement, in fact, is most satisfactory for the southern half of the model bay, except just where the waves curl round the breakwater. Here the graphical integration obviously fails to interpret wave-curvature correctly, the true waves being markedly retarded in their expansion round an obstacle. The uncovering of the reasons for this would provide a profitable theme for research: needless to say, the author had not the time or opportunity for going into this matter, but assumed that the model waves would in any case follow the true course of the prototype swells in the bay.

It is as well to note from this that the graphical analysis of seiches, as described in the last section, will be affected to some extent by the failure of the graphical process to represent the true refraction of waves round sharp corners, such as the end of the breakwater. The general results presented in the last section will not be invalidated, however, for they will still approximate to the true conditions, and they will have served their purpose in demonstrating the mechanism of the action taking place.

The important point to which we would draw attention at the moment is that the model bay is capable of refracting waves, as generated by the paddles, in much the same way as swells are refracted in the real bay.

It was reasoned, then, that, if the entire body of water in the model bay were set in commotion by some means, the resulting oscillations measured at the head of the bay should be indicative of the natural modes of oscillation of the prototype bay. To test this out the wave-paddles were stopped and the water in the model allowed to become entirely placid before slewing one paddle in its well from one limiting position to the other. When this was done as rapidly as possible against the considerable resistance of the water, it was found that strong seiches developed over the entire bay, but particularly in the harbour area, both inside and outside the basins. Fig. 121 is a typical Kymatograph model-recording of these seiches, at the root of the Eastern Mole outside the harbour, and in the Alfred Basin, for both clockwise and anti-clockwise rotation of the west paddle. Fig. 118 depicts the boundary conditions following upon clockwise rotation of the west paddle, and Fig. 119 the somewhat different boundary conditions after anti-clockwise rotation of the same paddle.

Analysis of the kymatograms (model wave-records), by Residuation, revealed the existence of the periodicities given below in Table VIII (converted to the natural time-scale):

Table VIII: Apparent Natural Periods of Table Bay from Model Experiments.

Paddle	Rotation	Apparent Periodicities (Minutes)											
West	Clockwise	—	53	—	28	—	16.7	12.0	7.8	6.3	5.7	4.7	—
West	Anti- "	58	—	—	31	23.1	14.4	11.5	7.5	—	5.3	5.0	3.6
North	Clockwise	—	—	39	29	19.3	12.0	11.2	—	—	5.6	4.7	2.0
Nobth	Anti- "	—	—	38	—	21.6	—	11.6	7.2	6.0	5.7	—	—

We cannot but be struck by the fact that the above periods accord closely with those reflected in both Tables IV and VI (pp. 257, 263), and this circumstance affords a means of enquiring further into the nature of the oscillations of Table Bay.

The identification of 53 and 58 minute oscillations in the west-paddle rotation-tests is of considerable interest in the light of the discussions on p. 266. With clockwise rotation, the ultimate paddle position shown in Fig. 118 must be assumed to have coincided with the node of the 53-minute seiche, the flux across the node being taken up by the water in the well behind the paddle. In much the same way the 58-minute seiche arising from anti-clockwise rotation of the west paddle, would be the fundamental oscillation for the bay with the node in line with the west paddle, in its ultimate position shown in Fig. 119.

In the north-paddle rotation tests, the west paddle was set parallel to the edge of the moulded sea-bed in its central position of symmetry, and the 38/39 minute oscillations recorded were probably associated with a node along a line directly between Mouille Point and Robben Island, as envisaged in Cases 2°, 3° and 9° (Table VI). For the rest, the periodicities conform well to the calculated periods for Case 1° in Table VI, the 29-minute seiche obviously being the uninodal oscillation in the longitudinal direction.

It would seem that the calculations of Table VI, taken collectively, are a fair measure of the periods of the natural modes of oscillation of Table Bay, and the general congruency of results as between the Tables IV, VI and VIII, respectively for observed, calculated and experimental periodicities, is most gratifying.

The paddle-rotation experiments were always very fascinating to watch, for they simulated very closely the conditions that prevail in Table Bay during occurrences of long-period seiches. The surging through the harbour basin-entrances, described in Section 50, (p. 146), is faithfully reproduced on a model scale, and, once induced, continues for long periods before dying away, much as it does in nature.

CHAPTER XIII

THE MECHANISM OF RANGE-ACTION.

> "There is a path that leads to truth so surely, that anyone who will follow it must needs reach the goal whether his capacity be great or small. And there is one guiding rule by which a man may always find this path, and keep himself from straying when he has found it. This golden rule is ___ give unqualified assent to no propositions but those the truth of which is so clear and distinct that they cannot be doubted".
>
> ——— Thomas Huxley,
> 'On Descartes Discourse
> on Method'. (1870).

95. The Breakwater-Shore Oscillating system.

It is patent from the considerations of the last chapter that Table Bay has a natural mode of oscillation of periodicity very close to 11 minutes. In terms of Case 1°, (p. 261) it could be closely linked with a quadrinodal seiche in the longitudinal direction of the bay, or in terms of Cases 4° and 5°, with an oscillation about a nodal diameter and a nodal circle. The condition is probably best represented by Cases 5° and 7°, but particularly 5°, where the nodal diameter might be considered to lie between Mouille Point and Robben Island, and the nodal circle or semi-circle to run parallel to the coast, or concentric with it, and intersect the Eastern Mole at right-angles, along the lines of the standing-wave system shown in purple in Fig. 114. With the complications, of course, of the open channel to the north of the bay, the true 11-minute seiche loses much of this elementary configuration and assumes the curved node of the resultant shown in Fig. 116. The important point, however, is that an 11-minute seiche is resonant for Table Bay, and would be, even in the absence of the breakwater and the harbour*.

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* This is largely confirmed by the fact that the Krakatoa sea waves in 1883 gave rise to prominent 62 and 10-11 minute oscillations in the harbour of that day (see Fig. 2, 1877, and p. 98 ante).

It is a singularly unfortunate fact, therefore, that the breakwater should have been so located in the scheme of things as to coddle this particular natural frequency by specially creating for it between the breakwater and the shore a further oscillating basin where it can resonate and reproduce its own family of dependent frequencies. It is for this reason that we are prepared to uphold the views of Robb and others (cf. p. 14) that Coode made a supreme mistake in selecting the present side for the breakwater. Had it been placed at Mouille Point where the nodes of the fundamental oscillations for the bay are situated in any case, there would not have been this danger of stimulating the higher-frequency seiches with their attendant Range-troubles. This is not to say that Range-action could thereby have been entirely avoided, but it would have been very much more subdued than it now is.

It is axiomatic that a harbour should preferably be located at the entrance to a bay rather than at the head of the bay for the avoidance of high-frequency oscillations and serious Range-effects. The reason for this lies in the fact that the nodal and antinodal lines for the higher-harmonic natural-frequencies of a bay tend to concentrate ever closer together as the head of the bay is approached, and it becomes almost impossible to avoid placing a sea-wall or harbour construction-work that does not foster one or other of these higher frequencies. At the mouth of the bay, on the other hand, the nodal lines are far apart and even if the harbour should fall foul of a node or antinode, the long periodicities of the lower modes of oscillation and their smaller amplitudes in deeper water would leave it relatively free of ill effects.

In the case of Cape Town, not only does the breakwater provide a further oscillating basin for the 10 or 11 minute seiche, but also for the 20-22 and $5\frac{1}{2}$-minute ones, which, according to the evidence of Tables IV, VI, and VIII, are, on their own account important natural periods for the bowl of the bay. Nor is this all, for the 9.5 and 4.7-minute seiches, as well as the 13.0 and 6.5-minute ones (cf. Table VI), find in the breakwater-shore oscillating system a receptacle in which they can attain near-resonance.

Once an oscillating basin has been created it can be expected to respond to its own particular natural frequencies, whose periodicities will not be far removed from an harmonic series, where, as at Cape Town, the depth of water is sensibly the same or reduces only slowly towards the shore. In the knowledge then that the fundamental oscillation for the breakwater-shore quasi-basin is 11 minutes, we could expect the harmonics in the series: $1, \frac{1}{2}, 1/3, \frac{1}{4}, \ldots$ to be 5.5, 3.7, 2.8, 2.2, 1.8, 1.57, 1.38, 1.22, 1.10, 1.00, 0.92,.... Similarly, the higher harmonics for the 13/6.5-minute and 9.5/4.7-minute combinations of forced seiches would yield their own harmonic trains to add to, or reinforce, the possible modes of oscillation of the watermass in the harbour area.

The 20-22 minute seiche, which, as we noted in Section 92 (p. 268) and Fig. 113, tends to have a node in line with the breakwater, may be likened to the fundamental seiche for an open basin with the node at the mouth. It will therefore tend to beget higher harmonics in the odd modes only, with one node always lying in line with the breakwater. In this way we should expect periodicities in the series: 1, 1/3, 1/5, 1/7, ..., namely, 7.3, 4.5, 3.1, 2.4, 2.0, 1.69, 1.47, 1.30, 1.16, 1.04, 0.96, ...

The co-existence of these several seiches for Table Bay and their developed families should then produce, upon coalescence, the average periodicities shown at the foot of Table

IX, in the immediate vicinity of the harbour.

Table IX: Natural and Forced Periods of Oscillation for the Breakwater-Shore Quasi-Basin.

Forcd. Oscil.	Higher Harmonics (Minutes).														
22	7.3	___	___	4.5	3.1	2.4	2.0	___	1.69	1.47	1.30	1.16	1.04	0.96	
13	___	6.5	___	4.3	3.2	2.6	2.2	1.86	1.63	1.44	1.30	1.18	1.08	1.00	0.93
11	___	___	5.5	___	3.7	2.7	2.2	1.83	1.57	___	1.38	1.22	1.10	1.00	0.92
9.5	___	___	___	4.7	3.2	___	2.3	1.90	1.58	___	1.36	1.19	1.05	0.95	
All	7.3	6.5	5.5	4.5	3.4	2.6	2.2	1.86	1.61	1.45	1.35	1.19	1.07	0.96	

The mean periodicities tabulated in the last row of Table IX have been derived by weighting twice in favour of the 11-minute seiche, to make some allowance for its more perfect resonance in the breakwater-shore quasi-basin.

These figures, which are capable of some fluctuation up or down, may now be compared with the apparent periodicities identified by residuation of the seichograms for the harbour area. The agreement is so good, that again we cannot ascribe it to mere chance; but before we draw any final conclusion on this matter we may profitably refer again to the results of the model experiments for verification, or otherwise.

96. Periodograms for the External Harbour-Area from Model Tests.

In the process of determining the best adjustments for the wave-paddle machinery of the model, during which the paddles were operated at various speeds or periodicities and their eccentric radii or strokes varied in an approximately uniform fashion, it was discovered that the amplitudes of the resulting oscillations in the harbour-area varied in a manner which could not be attributed merely to the paddle adjustments (Fig. 122).

Eventually it dawned upon the author that the model was responding to its natural frequencies. From this the idea was conceived of making the model trace its own periodogram, simply by operating the paddles at successively increasing periodicities and measuring, for each adjustment, the amplitudes of the effects in the harbour area.

Two somewhat imperfect tests along these lines were conducted on the model at the end of 1945 - imperfect in the sense that the paddles were subject to rather too much whip from over-flexibility of the shafting. This defect was later remedied, but as the full range of frequencies covered was not again tested, we give the results in Figs. 123(a) and (b) for what they may be worth. The second experiment aimed at determining the natural frequencies of the breakwater-shore oscillating system, and, to eliminate any effects from the harbour basins, their entrances were sealed. Amplitudes were measured at four points between the breakwater and the shore, whose locations may be identified in Fig. 109 from the co-ordinates given in Fig. 123(b).

The periodograms for each measuring point are recorded in Figs. 123, in which the remarkable increase in amplitude of the oscillations at certain periods is at once evident. As might be expected the maximum effects are found at the extremities of the oscillating area, while in between, where nodes occur at the recording points, certain of the peak periodicities are absent or subdued. By taking the envelopes of the peak periodicities (shown in red) and ignoring amplitudes, which are probably unreliable, we can obtain some idea of the natural frequencies of the area. In order of diminishing values, the following are the critical periods:

τ = 13.2, 11.5, 10.0, 9.0, 8.0, 7.2-6.8, 6.4, 6.0, 5.4, 4.8-4.5, 4.2, 3.6-3.4, 3.2, 2.8, 2.4-2.2, 2.0-1.9, 1.7-1.6, ... minutes ——————— (35).

These figures, insofar as their range extends, are very good confirmation of the periods found in Table IV and of the interpretations placed upon them in Table IX, as also of the calculated periods given in Table VI. The interpretations of Table IX are perhaps incomplete and may require the inclusion of other fundamental forced oscillations, which in terms of Tables IV and VI, seem to exist from time to time.

But later experiments, having reference more particularly to the interior of the harbour basins, afford us more material for judging of the critical periods in the important range from 1.0 to 8.0 minutes.

97. Periodograms for the Harbour Basins from Model Tests.

We anticipate the model researches once again to give here the results referred to, which are necessary to a full understanding of the Range-phenomenon.

Once the appropriate paddle-settings for the model had been worked out, an experimental search was instituted to discover the critical periodicities for the model harbour-basins. The tests involved recording the water oscillations at four different points in the model harbour for some 80 different wave-periods taken in succession. Each set of observations was repeated four times to simulate the effects of waves from four directions in the outer ocean, south-west, west-south-west, west and west-north-west, the paddles being appropriately slewed or altered to cover these cases. This work alone entailed the measurement and plotting of some 4000 observations, which are embodied in the composite periodograms of Figs. 124(a) and (b).

The results plotted in these diagrams have been corrected both for the variable frequency response of the recording Kymatograph, to which we shall refer in due course, and for the distortional effects of the model, to which we shall also allude at a later stage. The range or double-amplitudes of the oscillations have been plotted against a logarithmic time base: reduced to natural proportions, they far exceed anything yet measured in the harbour. This exaggeration, however, does not detract from the usefulness of the results, which should be interpreted on a comparative basis only.

The first thing we may notice from Figs. 124 is the relatively isolated frequency-bands of response in all the basins. The second thing is that, by and large, there is not a great deal of difference in this response for waves from the different directions. The critical periods are in all cases much the same; only the overall magnitude of the disturbances is appreciably affected by the wave direction.

In the Duncan Basin (Fig. 124(a)), there are two well defined bands of critical periods, the lower covering a range from about 1.3 to 2 minutes, and the upper from 4.3 to 8 minutes. In between there is a minor critical band from about 3.2 to 3.8 minutes. In the Victoria Basin(Fig. 124(b)), there are not such obvious zones of critical periods, although there are several important peaks. The Alfred Basin is not susceptible to the smaller periodicities, but responds powerfully to periodicities in the range from 4 to 8 minutes, a fact already noted in respect of the prototype harbour (cf. p. 64).

For reasons which will be made clear later, the subsequent experiments on the model, in the search for solutions to the Range problem, were all made with paddle-settings as for waves from the west-north-west direction outside Table Bay. In the course of these experiments it was necessary from time to time to re-examine the critical periodicities for the Duncan Basin (which formed the main subject of study) and to derive its periodogram of natural frequencies. Although the tests were always performed as nearly as possible under identical conditions, it was found that the basin exhibited rather temperamental characteristics, and would respond on different occasions to slightly different frequencies. The extent of this aberration is shown in Fig. 125, which gives superimposed periodograms for the four corners of the dock, corrected in periodicities for the distortion of the model, but not adjusted for slight variabilities of amplitude.

Although the period differences are not very great, they are nevertheless perplexing, and, for want of any better explanation, it must be supposed that they arise as the result of slight differences in the depths of water and minor deviations in the configuration of the coastline on the various occasions. Here it is necessary to add that the sea-bed in the vicinity of the model harbour was moulded in sand and profiled with removable templates, so that small divergencies in this way were unavoidable.

Taking the periodograms of Figs. 124 collectively, in conjunction also with those of Fig. 125, and grouping the peak periodicities wherever they are closely knit to form a solid band, we may descry what are obviously critical periodicities for the breakwater-shore oscillating system. If we discount the apparent unimportance of minor peaks, which probably derives from the unresponsiveness of the basins to those modes of external oscillation, the critical periods take the following sequence of averages, which should be interpreted as capable of limited fluctuation either way dependent largely on the direction of approach of the disturbing ground-swells, and the number of co-incident or nearly-coincident component seiches:

$$\tau = 7.5,\ 6.6,\ 6.0,\ 5.5,\ 4.7,\ 3.5,\ 2.6,\ 2.3,\ 1.81,\ (1.72)\ 1.60,\ 1.40,\ 1.33,\ 1.20,\ 1.07,\ 0.95,\ \ldots \qquad (36)$$

This series, compared now with Tables IV, VI and IX, but especially the latter, shows excellent correspondence, and not only establishes the worthiness of the model, but confirms the interpretations we have placed upon the existence of these seiches in the harbour area. There is, however, at least one notable omission in Table IX in respect of the 6.0 minute periodicity, and it would appear that a 12-minute fundamental forced oscillation should have been included in its assembly. The 8.0 minute frequency found in the rather imperfect experiments leading to the results of (35),(p. 283), is not in evidence in Figs. 124, but a 1.72-minute seiche now looms somewhat inconsistently in the picture. The significance of this in relation particularly to the Duncan Basin will be discussed in the next section. In all other respects the critical periodicities of (36) substantiate (35) and Table IX.

98. The Natural Modes of Oscillation of the Completed Duncan Basin.

We come now to consider the manner in which the seiches of the breakwater-shore system are communicated to the Duncan Dock, the most important basin of the harbour at Cape Town.

As the basin is vertical-walled, of very regular shape, and of almost uniform depth, it provides a very good case for the application of the hydrodynamical equations developed in the last chapter. We may therefore examine its natural frequencies in the light, first of all, of equation (18), on the assumption that it is entirely closed.

The length of the basin for all practical purposes is $L = 6000$ ft., and its depth $d = 40$-45 ft., according to the state of the tide. The breadth of the basin at the north-western end is $B = 2100$ ft., but for three-quarters of its length towards the other end it is $B = 2200$ ft. Fitting these data to equation (18) yields the following:

Table X: Natural Periods of Duncan Basin from Hydrodynamical Theory.

Direction	Dimensions		Computed Periods (for values of m) -Mins.							
	L or B	d								
Length	6000	40	5.57	2.78	1.85	1.37	1.11	0.93	0.79	....
		45	5.26	2.63	1.75	1.31	1.05	0.88	0.75	....
Breadth	2100	40	1.95	0.97	0.65	0.49	0.39	0.33	0.28	....
		45	1.84	0.92	0.61	0.46	0.37	0.31	0.26	....
Breadth	2200	40	2.04	1.02	0.68	0.51	0.41	0.34	0.29	....
		45	1.93	0.96	0.64	0.48	0.39	0.32	0.28	....

Besides the natural periods shown in Table X, there will be a mode of oscillation in which the northern end of the basin opposite the entrance acts transversely as a canal, open at the mouth. The applicable equation in this case is (29), (p. 244), from which, for $s = 1$, the natural period will be double of the periods of the fundamental seiches in the transverse direction given by Table X; namely, from 3.68 to 4.08, according to the height of the tide.

For a rectangular basin in which propagation is two-dimensional, as it will be in the Duncan Dock, there will be other modes of oscillation dependent upon the length-breadth ratio, as given by equation (19), (p. 237). This ratio is very closely 3, so that β in equation (19), will have the value 9.

The natural periods already given in Table X correspond to the cases, taken separately, of $n = 0$ and $m = 0$; some of the remaining cases when m and n are both finite are investigated in Table XI:

Table XI: Natural Periods of Duncan Basin: Two-Dimensional Oscillation.

Depth d	Computed Periods (for different values of m and n)-Mins.									
	m = 1 n = 1	2 1	3 1	4 1	5 1	6 1	1 2	1 3	1 4	2 2
40	1.76	1.55	1.31	1.11	0.96	0.83	0.92	0.62	0.46	0.87
45	1.67	1.46	1.24	1.05	0.90	0.78	0.86	0.58	0.44	0.83

Only the first few important periods are incorporated in the above table, because other values of m and n tend to give overlapping periods which are either indistinguishable from those given or approximate to the values already listed in Table X.

We are now in a position to write down the critical periods for the Duncan Basin as it is today: these, on the average, form the series

$$\tau = \underline{5.4},\ 3.9,\ 2.7,\ \underline{2.0},\ \underline{1.85},\ \underline{1.72},\ \underline{1.51},\ 1.34,\ 1.28,\ \underline{1.08},\ \underline{0.98\text{-}0.90},\ 0.80,\ 0.66\text{-}0.60,\ 0.50\text{-}0.45,\ 0.33\text{-}0.30,\ \ldots\text{minutes.} \qquad \text{———} (37).$$

Underlined are the periodicities that are likely to be of greatest importance because of the special shape and dimensions of the basin, these being, in general, the lowest modes of the several kinds, longitudinal, transverse and two-dimensional.

99. The Excitation of Seiches in the Duncan Basin.

As to whether these natural frequencies will ever be excited depends essentially on the nature of the disturbances infiltrating from outside the basin. Reference to Table IX (p. 281) shows that many of the periodicities of the seiches which have been proved to exist in the external oscillating basin between breakwater and shore are very close in value to the natural periods of (37). The 5.5 and 1.86 minute seiches outside the Duncan Basin are almost exactly tuned, and if the antinodal positions are favourably situated to cause a flux through the basin entrance, they will induce completely resonant oscillations inside. The external seiches of periods nearest to these critical values can also be expected to beget forced seiches of near-resonance.

The model tests reflected in Fig. 124(a) prove that the 6.0 and 4.7-4.5 minute external seiches can obtain a fair measure of response from the Duncan Basin. Their co-existence, in fact, would be likely to produce a beat oscillation with an apparent periodicity of about 5.3 minutes, (as explained in Section 85 (p. 246)), which would strongly reinforce the main 55 minute forced seiche. The longest periodicity recorded in the Duncan Dock in any given case would depend on how many of these three forced seiches were present outside. If the 6.0 minute seiche were absent, for instance, the 5.5 and 4.6 minute seiches would tend to promote a beat oscillation of about 5.0 minutes period inside the basin, whereas if the 4.6-minute one were missing, the apparent periodicity would run to about 5.8 minutes or possibly higher. On rare occasions, no doubt, one or other of these forcing seiches might operate alone and impress its own periodicity upon the basin.

Direct and convincing evidence of the combining of the forced seiches in beats is provided by some of the seichograms of Figs. 51, 52 and 53. Attention is drawn in particular, in these reproductions, to the very obvious beats occurring simultaneously in the oscillations at A and E berths in the Duncan

Basin. In Section 48 (p. 142), we showed that these gave evidence of a fundamental transverse oscillation across the dock at the northern end, but if we analyse them further in term of equations (33), (p. 248), we can uncover the true constituent periods.

Thus in Fig. 51, the average length of the beats is 11 minutes and the apparent periodicity of the oscillations 1.765 minutes. The beat frequency is thus $\omega = 2\pi/22$, while $p = 2\pi/1.76$. From equations (33), therefore, the component periods are found to be $\tau_1 = 1.63$ and $\tau_2 = 1.92$ minutes.

In Fig. 52 the beats are a little longer (14.5 minutes) and the average period of the apparent oscillation is 1.722 minutes, making $\tau_1 = 1.63$ and $\tau_2 = 1.83$. Fig. 53 again yields a beat length of 12.2 minutes and an apparent period of 1.700 minutes, to give components $\tau_1 = 1.59$ and $\tau_2 = 1.82$ minutes.

These three cases then reveal that the 1.86 and 1.61 minute forced-seiches of the breakwater-shore system (Table IX) are generally co-existent, and together create a periodicity of about 1.72 minutes, which is resonant for the Duncan Dock, as shown in (37).

If we scrutinise the latter part of Table II, from about the middle of 1945 onwards (p. 135), we find evidence (from the marigrams of the Lea tide-gauge at E/F berths) to corroborate these findings. The fundamental longitudinal seiche is strongly in evidence in that part of the dock and fluctuates in periodicity from about 5.2 to 6.0 minutes. The transverse seiche there is sometimes pure and sometimes combined, to give periods between 1.72 and 1.88 minutes.

The theoretical approach (Table XI) now explains the occurrence of 1.72 and 1.55-minute critical periodicities in some of the periodograms of Figs. 124 and 125. These are the most important two-dimensional natural frequencies for the Duncan Basin, and are easily brought into vibration by the outside disturbances if for any reason there is a slight shortening of the periodicities of the usual 1.86 or 1.61-minute forced-seiches. Changes in swell-direction and tide-height can presumably bring this about, for we find evidence in Table IV (p. 257) of some of these oscillations. For the most part, however, to judge from Table II, it is the 1.86 and 1.61-minute seiches that prevail, and combine to give a 1.72-minute oscillation. The 1.61-minute frequency is not often found on its own, and this is no doubt because it becomes merged with its stronger partner, whenever it builds up in amplitude, and completely loses its identity to the latter when it weakens.

Intermediate between the longitudinal and transverse fundamental seiches in (37), we find natural periods of 3.9, 2.7 and 2.0 minutes. The first is, indeed, in evidence in Table II (latter part) and Table IV, and is found also in the model periodograms, being obviously activated by the 3.4 minute external seiche of Table IX (p. 281.) The 2.7-minute oscillation, on the other hand, is rather conspicuously absent. The reason for this must be conjectured, but is not difficult to explain.

In the first place the 2.7-minute frequency is the second harmonic or binodal oscillation for the basin in the longitudinal direction, and, as such, has nodes at the quarter-points. The location of the basin entrance, however, is also situated at the eighth-to-quarter point in the long side of the dock, and therefore coincides with a nodal area of the second harmonic. No amount of stimulation from outside can then excite this mode of oscillation even though, as we have seen, a 2.8-minute seiche is prominent outside the harbour. In much the same way, a periodic force applied at a nodal point of a stretched string, cannot animate the particular mode of oscillation for which the string is nodal at that point, despite the period of the force being resonant with it.

In terms of Table X, the 2.0-minute natural frequency of (37) is really the fundamental transverse oscillation for the southern end of the dock. Figs. 124 and 125, however, show that, although it is excited at that end of the dock, it is in rather subdued form. This is no doubt because the 2.3 minute forcing seiche outside the basin is somewhat out of step and is only able to impose upon this mode of oscillation by forming a beat frequency of the right order with the 1.86-minute seiche.

Below the 1.51-minute natural frequency in the periodic scale of (37) we have natural periods of 1.34, 1.28, 1.08 and the important group between 0.98 and 0.90 minutes. All of these are to be found in Table IV and Figs. 124 and 125, and as they correspond with the external forcing seiches of Table IX, their generation is satisfactorily explained. All oscillations approaching 1 minute in period may be considered to be binodal transverse seiches.

There is not much corroborative material to confirm the natural periods below about 0.9 minutes, other than is contained in Table IV, but this on the whole is favourable. The interpretation of most of the periodicities detected in the records for the Duncan Basin, given above, thus appears to approximate to the truth.

100. The Changing Natural Frequencies of the Duncan Dock.

The explications for the observed commotion in and round the harbour thus far fit in with the facts as we know them today. If they also account satisfactorily for the variable behaviour of the Duncan Basin during its construction, we shall finally know them for the truth.

The changing conditions in the Duncan Basin were referred to in Section 46 (p. 133) and are fully reflected in

Table II (p. 134). The general explanations for the varying periodicities have already been given in that section and need not be repeated here, except insofar as they require substantiation.

The Lea-gauge marigrams at the E/F berth location in the Duncan Dock showed in 1940 two principal longitudinal oscillations, besides the now familiar transverse oscillations. These ranged from about 7.6 to 6.8 minutes and from 4.9 to 4.2 minutes (p. 134), and were clearly distinguishable in these categories.

The Duncan Dock at that time was in course of construction and had not as yet assumed its rectangular form. Its specific shape can be gauged from Fig. 10 as something intermediate between the outlines of November, 1939, and November, 1941. Essentially, therefore, it was a long basin, square-ended and vertical-walled at the north-western extremity, but oblique-ended at the opposite boundary, which shelved from the reclamations there with the steady gradient of the virgin coastline. Only the north-western end of the basin, about 2000 ft. square (the full width of the basin), had been dredged to a depth of 40 ft. below LWOST.

This basin, of course, was flanked on the southern side by a large lagoon of water, then being reclaimed from the sea, the mouth of which was beginning to be constricted by the advancing quay-wall construction from the north and the reclamation deposits from the south.

For this shape of basin we have no really dependable formula for computing the fundamental mode of oscillation, but we may hazard a guess by applying equation (20) (p. 238), which Chrystal found so useful in estimating the natural periods of lakes of all shapes of outline and depth. For this we ignore the lagoon and take the mean length of the basin along its axis, $L = 7200$ ft., and its maximum depth, $d_0 = 40$ ft. Equation (20) then yields $\tau_1 = 7.5$ minutes for $m = 1$ and $\tau_2 = 4.3$ minutes for $m = 2$, which, considering the poor approximation of the parabolic bed of the formula to the true sectional profile of the basin, are not bad tallies with the observed periods.

Another estimate for the fundamental mode of oscillation is possible using the graphical method which has proved its worth and accuracy in earlier sections of this chapter. Thus, in the knowledge that the bed of the Duncan Basin at that time was largely the undisturbed sea-bed of the bay, we may define two points, (L, 35) and (P, 40), on the co-ordinate network of Fig. 109, whose distance apart is about equal to the length of the basin from the square end to the farthest extremity, between which the water depths and bed-gradient are much the same as those of the basin. The line joining these points is about parallel to the axis of the basin and at right angles to the wave-fronts crossing them, so that we have in effect displaced the basin parallel to itself into a zone of the diagram where wave expansions have been plotted.

The fundamental period of the basin will then be twice the time taken by a ground-swell to travel from one point to the other, which from Fig. 109 is $\tau = 2(14.1-10.5)$ or 7.2 minutes at low tide. At high tide this figure would be reduced to about 6.9 minutes, giving a range in good general agreement with Table II (p. 134). This then leaves no doubt but that the longest periods for 1940 in Table II correspond to the lowest mode of oscillation for the basin, whose development could logically be ascribed to the 7.3-minute external seiche of Table IX (p. 281).

By the end of 1941, Table II reveals that this lowest mode of oscillation had altered somewhat to give slightly shorter periods from about 6.9 to 6.0 minutes. Fig. 10, however, shows that beyond having its south-eastern end lined with a revetment-wall, the basin had not altered appreciably in overall size from what it had been the year before. But the dredging of the basin had been proceeding apace and a length of about 3000 ft., or half the ultimate length of the basin had been cut to a depth of 40 ft. at LWOST. It is not difficult to see then that, as periodicities of oscillation in general are inversely proportional to the square root of the depth, the diminution of the periods was caused by the deepening of the basin.

The secondary oscillations of periods from about 5.0 to 4.2 minutes persisted apparently unchanged throughout 1940 and 1941, and we must seek to account for this by reference again to model tests.

In preliminary trials of the model which aimed at proving it, the conditions of November, 1941, (Fig. 10), were accurately reproduced, the lung formed by the lagoon of water on the southern side of the basin being included. The model was operated for the conditions of waves from the west-north-west direction, and the results of the experiments are contained in the periodograms of Fig. 126.

Two bands of critical periods show up in these periodograms, the larger of which incorporates several peaks. These may be identified as frequencies of 7.1, 6.6 and 6.2 minutes period, together with minor ones at 6.0 and 5.5 minutes. The latter, which we know to be a strong external seiche, in existence always when ground-swells run into the bay, was barely able to influence the basin at that time.

We may recognise in all these periodicities the now familiar sequence of Table IX (p. 281) with the addition of the 6.0 minute seiche, which the considerations of Section 97

(p. 286) showed to be necessary of inclusion. These particular forcing seiches are most nearly tuned to the natural frequencies of the basin as it then was, and draw the maximum response.

The smaller band of the periodograms giving a peak at 4.3 minutes corresponds again almost exactly with the observed periods of Table II, and in terms of the approximate calculation on p. 294, must be interpreted as being the second harmonic or binodal oscillation for the basin. As mentioned in Section 46 (p. 137), however, this mode of oscillation was observed to involve the lagoon in a joint three-cornered flapping of the whole cloverleaf-like body of water, contained by the Eastern Mole. An antinode was in evidence at the junction of the lagoon with the basin, common to all three petals of the clover-leaf formation. There were thus three nodes, one in each petal, two of which, of course were roughly transverse to the basin and thus accorded with the binodal longitudinal oscillation of that body of water on its own. The motivating seiche in the external breakwater-shore oscillating system was obviously the 4.5-minute one of Table IX.

In 1942 the quay-wall construction and reclamation works met and sealed off the lagoon of water to the south of the basin (Fig. 10). The works for the construction of the graving dock at the south-eastern end of the basin meanwhile gradually pushed out and finally cut off the triangular-shaped end. The closing of this area by cofferdam must have occurred towards the end of July, 1943, to judge from the sudden disappearance of the mode of oscillation of 7.1-6.2 minutes in the marigrams of the Lea tide-gauge (Table II, p. 135) and this was indeed the case (Fig. 10). But here we have to explain the enigma of the persistence of the 4.3-minute seiche in the face of this shortening of the basin and the detachment of the lagoon, and, particularly too, of the absence of any 5.9-5.0 minute oscillations in 1944, such as showed up subsequently in 1945.

It is necessary to record that by 1943 the dredging and rock-breaking in the basin had extended the 40 ft., depth of the bed at LWOST to two-thirds of the finished length of the basin. Of the remaining one-third length about half had been dredged to between 38 and 35 ft., while the remaining length at the southern end formed a shelf only 20 ft. deep. In effect then the dock consisted of a submarine basin of effective length $L = 5000$ ft. and depth $d = 40$ to 45 ft., with a shallow platform at the end rising up to the cofferdam that embraced the graving dock construction.

If this shallow platform be ignored and the data are fed to equation (18), (which is applicable to the conditions), we find the fundamental periodicity to be $T = 4.6$ to 4.4 minutes according to the height of the tide.

An examination of the conditions as in November, 1943, was undertaken in a further proof-test of the model, which led to the periodograms of Fig. 127. These confirm the theoretical indication of a strong band of critical periodicities at 4.6 minutes, but they also show that there is considerable response to the forcing seiches in the immediate lower modes (5.5, 6.1, and 6.6 minutes). However, for the particular location of the Lea tide-gauge, the latter periodicities are very subdued (Fig. 127), and to this fact very largely must be ascribed the absence of any indications of them in the marigrams for 1944 (Table II, p. 135).

There was, nevertheless, another factor affecting the issue which only came to the author's attention long after the experiment. This concerned the deposition of the dredgings from the basin in a wide area outside the Eastern Mole. A considerable shoal formed here, which must have had a profound effect upon the seiches of the breakwater-shore oscillating system. When the extent of the shoal was discovered it was realised by the harbour authorities that it constituted a hazard to ships in the roadstead, and it was by degrees removed.

Although the author at this stage has no factual information to go on, he is of the opinion that the total disappearance of any 6.0-5.3 minute oscillations in 1944, and their reappearance in 1945, is intimately bound up with the growth and final removal of this sandbank outside the harbour.

By the end of 1944 the Duncan Basin had been dredged to its designed depths throughout most of its area except that immediately adjoining the cofferdam of the graving dock, but in April, 1945, the removal of this cofferdam was commenced, and by June the basin had to all intents and purposes assumed its completed form. The slight diminution of periodicity that might be expected of this final deepening seems to be in evidence in Table II (p. 135), culminating in the complete cessation of the 4.3 minute frequency and its replacement on rare occasions by the less stable 3.9-3.7 minute transverse oscillation.

The Duncan Basin has afforded us a beautiful example of the influence of dimensions and depth on the oscillating characteristics of an enclosed body of water. In all the time of its construction the seiches of the breakwater-shore quasi-basin, in themselves largely unchanged, have played upon the water-mass of the Duncan Dock often with completely different results. It has, we believe, been conclusively shown that in such circumstances a basin will only respond to those impressed frequencies which accord most nearly with its own. Partial resonance seems to be possible when the forcing seiche is sufficiently ~~close~~ CLOSE IN in period to that of the natural frequency, and this is fully substantiated on theoretical grounds, there being no precipitate transition from complete unresponsiveness to full resonance. The explanation we offered in respect of some of Chrystal's observations on forced seiches (p. 242), now seems to be justified by the facts.

101. Oscillations of the Victoria and Alfred Basins.

Considerations of space preclude our discussing complete details of the oscillations that are peculiar to the Victoria and Alfred Basins, but some discursive remarks seem necessary in passing.

The behaviour of these basins follows the same general mechanism as the Duncan Basin, their response, of course, depending upon the shapes and sizes of the individual compartments into which these docks are divided. The periodograms contained in Fig. 124(b) are generally indicative of the critical frequencies as they are inspired by the external forcing seiches.

It will be noticed from Fig. 124(b) that the peaks of maximum amplitude occur at periodicities of 6½ minutes for the Alfred Basin and 4½ minutes for the Victoria Basin. It is of some interest that these are fairly close to the periods cited in Section 52, (p. 150), for the seiches which would produce in the entrances of these basins the same velocity of flux per unit amplitude of seiche as would an 18-minute seiche in the Duncan Basin.

We have seen that the lowest mode of oscillation for the Duncan Basin has a period of the order of 5.6 minutes. Any forced seiche of period longer than this must then cause a general rise and fall of the entire surface of the basin. The condition that the velocity of flux through the entrance should reach its maximum value, depends, as equation (13) (p. 150) shows, entirely on the maximum value of the ratio A/τ , and from observation it is generally the 18 to 22 minute seiches for the bay that provide the largest value for this ratio.

For equal amplitude, then, a 4½-minute seiche is to the Alfred Basin and a 6½ minute seiche to the Victoria Basin, what an 18-minute seiche is to the Duncan Basin; namely, these periodicities occasion a rise and fall of the entire water surface in these basins.

Model experiments show that this pumping action of the entire water-body starts in the Victoria Basin at periodicities above 4.0 minutes, and in the Alfred Basin at periods above about 3 minutes. In the case of the Victoria Basin it is not difficult to see why this should be so, since this dock is roughly square and of the dimensions of the width of the Duncan Basin. Any uninodal oscillation for the Victoria Dock must therefore be of the same order as the fundamental transverse oscillation for the Duncan Basin, which we found to be 1.85 minutes (cf. (37), p. 288). Fig. 124(b) shows this to be true. The mere doubling of this figure gives us the approximate periodicity (3.7 minutes) of the open-mouth oscillation, which is nodal at the entrance and increases in amplitude from the mouth to the head of the dock. Higher periodicities must therefore cause a more or less universal scend over the entire area of the basin.

102. Erosion along the Paarden Eiland and Milnerton Coast.

In the light of our findings, it is pertinent here to make some comment on the problem of the erosion of the shoreline of Table Bay which we referred to in Section 14 (p. 44).

We intimated there that there were aspects of this denudation of the beaches common to the phenomenon of Range-action, the implication being, of course, that the ground-swells and seiches which are responsible for the troublesome commotion in the harbour, are also responsible for the inroads of the sea upon the coast and the consequent destruction of the marine drive at Cape Town.

In Section 41 (p. 118) we drew attention to the destructive power of ground-swells, and it behoves us to enquire further into this matter. As ground-swells inevitably tend to form standing-waves and seiches, we may approach the subject by examining the water-particle movements in the horizontal direction, since these must be the main agents of destruction for which ground-swells are so notorious.

The horizontal displacement of a water particle at any point in a standing wave is given by equation (14)-(i), in which, as we noted on p. 108, the hyperbolic factor varies from $1/\text{Tanh}\, qd$ at the surface ($z=0$) to $1/\text{Sinh}\, qd$ at the sea-bed ($z=-d$). Provided the depth d is small compared with the wave-length of the standing wave, (a usual condition with ground-swells), this factor approximates to the value $1/qd$.

By differentiating (14)-(i) with respect to time and inserting this value for the hyperbolic factor, the horizontal velocity of a water-particle is found to be

$$\frac{\partial \xi}{\partial t} = -\frac{Ap}{qd}\cdot \text{Sin}\, qx \cdot \text{Cos}\,(pt+\epsilon) \qquad \text{(38)}$$

and its acceleration

$$\frac{\partial^2 \xi}{\partial t^2} = \frac{Ap^2}{qd}\cdot \text{Sin}\, qx \cdot \text{Sin}\,(pt+\epsilon) \qquad \text{(39)}$$

The maximum values of both velocity and acceleration occur at the node of the standing wave, where obviously $\sin qx=1$. They are also maxima at the instants in the period of the standing wave, when $\cos(pt+\epsilon)$ and $\sin(pt+\epsilon)$, respectively, are unity. By resolving the factors in equations (38) and (39) in terms of equations (2), (3), (5) and (8), (p. 107), the maximum velocity and acceleration will be found to be

$$\left(\frac{\partial\xi}{\partial t}\right)_{max} = A\,(g/d)^{\frac{1}{2}} \qquad (40)$$

and

$$\left(\frac{\partial^2\xi}{\partial t^2}\right)_{max} = Ap.(g/d)^{\frac{1}{2}} \qquad (41)$$

Equations (40) and (41) are illuminating. So long as the node of the standing wave or seiche occurs in water which is deeper than 32 feet, the maximum surge-velocity in feet per second does not exceed the value of the amplitude of the seiche in feet, (usually less than 2 ft.), but if the node runs into shallow water and in the limit into water of no depth at all, the velocity and acceleration, and therefore the transporting power, across the node become, theoretically, infinitely great.

If then it can be shown that the nodes of seiches enter very shallow water, we will have found a satisfactory explanation for the destructiveness of ground-swells.

In the case of Table Bay we have shown in our analysis of the 11-minute seiche which is prominent outside the harbour, that a node must clearly run into the coast at a somewhat oblique angle (Fig. 116), a little north of the Diep River mouth. Powerful surging must therefore take place over a wide frontage of beach in this area. But what is true of the 11-minute seiche is also true of its numerous higher harmonics, as Fig. 117 suggests, and we should expect therefore a number of nodal points along the coast where the inroads of the sea are particularly severe.

It is just such sporadic attacks that we find strongly in evidence all along the Paarden Eiland and Milnerton coast, even far beyond the Diep River mouth, as may be plainly discerned in the photographs of Fig. 79. It is therefore a reasonable conclusion that the seiches of the breakwater-shore oscillating system are major culprits in the undermining of the coast north of the harbour, and that this erosion may be expected to continue into the future, unless some other opposing forces come into play to balance the regime.

103. Review of the Mechanism of Range Action.

In Section 78 (p. 223) we epitomized the general origins of the phenomenon of Range-action on the premise that it consisted essentially of a combination of standing waves formed by entrant and reflected waves of translation impinging upon a coastline. It is necessary here to complete the composite picture of origin and effect by summarising the knowledge gained regarding the mechanism of the phenomenon.

Range-action can be said to derive mainly from ground-swells whose particle movements in the horizontal direction are virtually uniform from the free surface to the sea-bed (p. 117). In view of this the breaking of the wave on a shelving littoral cannot take place and the energy of the wave is not destroyed in vorticity and turbulence as is the energy of shorter waves which constitute the familiar surf. The ground-swell rushes up a sloping beach or swells up against a rocky escarpment as a surge which withdraws and propagates itself outwards from the coast as a reflected wave (p. 246).

The reflected ground-swell has the same periodicity and properties as it had previously and has a progressive motion which is either directly or obliquely opposed to that of other waves of the train, (of which it is a member), which may still be incoming.

The interaction of opposed waves of equal periodicity and nearly equal amplitude and energy content is a standing wave, the special properties of which comprise a synchronous mass-movement of the water-particles about a fixed node or vertical section, across which there is only horizontal movement. On opposite sides of the node the vertical movements of the body of water are opposed, in a sort of see-saw action with the node as a fulcrum. At the antinodes where the vertical movements are a maximum at the free surface, the horizontal displacements are all zero (p. 233). In the theoretical case where the amplitude of the reflected ground-swell has not suffered any diminution, the amplitude of the standing-wave becomes double of the component waves (p. 235).

When ground-swells run into bays or inlets where the coastline is irregular or curved, their reflections often converge inwards upon each other, interlace, and perhaps reflect again, if the topographic features favour it, to form further standing waves which augment the amplitudes of the water-movements in antinodal areas (p. 270).

A seiche may be considered as a special case of a group of standing waves which reinforce each other synchronously, through repeated reflections of the underlying ground-swells (p. 270). Were it not for the attrition and frictional effects, the superposition in this way of an infinite number of standing waves would result in a seiche of infinite amplitude. Fortunately friction and dispersion severely damp this tendency.

The seiches of open coasts are in essence no different from the seiches of enclosed bodies of water. The oscillations of inland lakes and ponds consist fundamentally of the opposed motion of equal systems of progressive ground-swells, which, in the lowest mode of oscillation, have a wave-length which is twice the length of the basin (p. 237). For any given length and shape of enclosed basin there are a number of seiches which can exist simultaneously, the only condition being that each have an antinode at the extremities of the basin. This condition gives such seiches a family relationship which is usually harmonic, (p. 237). The harmonics are distinguishable by the number of their nodes and by their frequencies, but while amplitudes usually decay with increasing nodality, there is not otherwise any restriction upon the amplitudes or phases of the harmonics.

Every enclosed or semi-enclosed body of water has natural periods of oscillation which depend entirely upon its dimensional characteristics such as the surface-configuration and the topographical features of the bed, as affecting the depth. The family of natural frequencies in the general case is not related in an harmonic series, this relationship being only a special case applicable to simple geometrical shapes, such as basins of rectangular form and uniform depth (p. 238).

Basins which open upon larger bodies of water have in general an entirely different system of oscillation, in which the natural frequencies all have nodes at the mouth (p. 244). The fundamental mode of oscillation in this case is occasioned by ground-swells whose wave-length is four times the length of the basin (p. 265). However, if the opening in the basin is comparatively small in terms of the dimensions of the basin, the latter will respond to modes of oscillation which are a combination of the modes for basins fully closed and fully open.

We have shown that ground-swells not only precede trains of wind-generated waves, but tend to traverse through them from their rear (p. 229), so that in any incidence of swell on a coastline there is usually a persistent undertow from the underlying ground-swells. The latter are of all periodicities, owing to their inherent tendency during propagation to attenuate (p. 214), and when a swell enters a bay or semi-enclosed basin, therefore, the periodic stimulants are on hand for generating the seiches peculiar to the special shape of the bay or basin. Those ground-swells which agree in period with the natural frequencies of the areas immediately resonate by inducing seiches: all other ground-swells merely form non-resonant standing-waves which lose all identity in the resulting commotion.

The spawning ground of the tempests and meteorological disturbances, where the waves that harry the South African coastline are begotten, is the large expanse of South Atlantic ocean south-west of Cape Town. We have shown that the ocean itself in this area lies in what is vitually a submarine basin, formed between the South African continent and the mid-Atlantic ridge, and flanked by a submarine rib on the northern side (pp. 38, 258). This rib or spur of rising ground also forms a triangular trough with the west coast of Southern Africa (p. 258), whose vertex lies near the mouth of the Cunene River and whose open mouth,fronting on the southern ocean, lies along a line due west of Cape Town (Fig. 7).

Not unnaturally, these oceanic basins respond to the pressure changes imposed upon them by the travelling depressions and the enormous water-masses oscillate ponderously, if minutely, in the many modes that are possible to them. We believe that we have uncovered indubitable evidence of the oscillations of the ocean not only in the submarine basin but also in the submarine canyon (p. 260). Although as yet undetected, because not specifically looked for,we venture to predict that there exist 460 and 350-minute seiches which are fundamental to these submerged basins.

The vast scale and majesty of these oceanic pulsations, which transcend even those that inspired Forel to the words of reverence we have quoted on p. 84, cannot but fill us with profound awe and something of the humble emotion felt by Forel himself, the 'Faraday of Seiches'.

Table Bay, whose likeness to an elliptic bowl has been portrayed in Fig. 8, lies at the boundary of the two oceanic oscillating basins and is therefore subject to forced seiches from their higher modes of oscillation. A forced seiche may be described as an oscillation, resonant in some external system (as the ocean in this case), which is impressed upon a body or basin of water whose natural periods of oscillation do not necessarily agree with it. In such circumstances there may be full or only partial resonance depending on the nearness of the impressed periods to the natural ones.

By a freak of chance, perhaps, Table Bay is able to resonate to many of the higher frequencies of the oceanic forced seiches (p. 267), but of its own accord it provides an echo-chamber for the resonance of wave frequencies which are too high to make any appreciable impression upon the oceanic water-mass (p. 267).

We have adduced evidence to show that Table Bay functions in many different ways, which seem to be a sort of composite of the modes of behaviour of rectangular, circular and elliptic basins with and without openings in their end and side (p. 264). The response of the bay on any particular occasion seems to depend very largely on the direction of approach of the ocean swells or of the overhead barometric oscillations. Owing to the interaction of the north and west channel-entrances to the bay, there is a tendency on occasion for some resonant frequencies to destroy themselves (p. 271):

a slight shift of the swell direction, however, may be enough to bring the same frequencies into full resonance.

The most important critical periods for Table Bay appear to form the series (Table VI, p. 263):

$\tau =$ 71-66-57, 55-51, 43-36, 33-26, 23-17, 14-12, 11-10, 9.8-9.4, 8.3-7.8, 7.5-7.0, 6.8-6.5, 6.3-5.9, 5.7-5.4, 4.8-4.4, 4.3-4.1, 4.0-3.7, 3.6-3.4, 3.2-3.1, 2.9-2.7, ... minutes. (42)

Just as the majority of the above frequencies cannot much influence the water-mass in the oceanic basins, so the highest frequencies of ground-swells, (not shown in(42)), cannot make much impression upon the water-body in Table Bay. It requires a still smaller oscillating basin to encourage the development of such seiches, and this, as it happens, has been provided by the handiwork of man, in the form of an open-sided basin between the harbour-breakwater and the opposite shore.

But unhappily for Cape Town the location of the breakwater has fortuitously fitted in with the forced seiches imposed upon the man-made basin by the oscillations of the bay. The forced seiches of Table Bay, in the higher modes, resonate almost perfectly in the breakwater-shore basin and thereby greatly stimulate themselves in that corner of the bay, besides ensuring the promotion of yet higher-frequency seiches.

We find then the critical periods for the breakwater-shore oscillating system complying generally with the following series, (Table IV and IX, (35) and (36)):

$\tau =$ 12-10.5, 9.7-8.7, 7.7-6.9, 6.8-6.3, 6.2-5.9, 5.7-5.3, 4.9-4.2, 3.7-3.1, 2.8-2.6, 2.3-2.0, 1.95-1.70, 1.65-1.50, 1.46-1.40, 1.37-1.31, 1.22-1.17, 1.10-1.05, 1.00-0.93, ... minutes. (43).

Comparison between the series (42) and (43) above will serve to show how good is the agreement between the seiches of Table Bay as a bowl or basin on its own and the seiches of the bight between the breakwater and the Paarden Eiland shore.

It is the existence of these seiches immediately outside the harbour that is responsible for the surging and Range-action inside the docks. We have shown that the seiches in the quasi-basin outside the port have nodal lines which tend to be normal to the harbour-boundaries along the line of the Eastern Mole (p. 273). At any particular point along this line, say at the entrance of the Duncan Dock, the water will rise and fall, or move to and fro, parallel to the Eastern Mole, in accord with the resultant motion given to the water-particles by the simultaneous operation of whatever seiches in the series (43) may happen to be in existence. Some seiches may be nodal at the entrance point we are considering, but others will inevitably be antinodal, and the rising and falling of water in their periods creates alternately a head of water outside and then inside the dock, which of necessity induces a compensating flux first inwards, and then outwards through the entrance, in the period of the seiche.

Once again, unfortunately for the harbour, the Duncan Dock was created with precisely the entrance location and dimensions which permit of full resonance of several of the forced seiches of the breakwater-shore system. Its length of 6000 ft. and average depth of 43 ft. ensures a perfect echo-chamber for the 5.7-5.3-minute forcing seiche, which we have seen is not only a natural seiche for Table Bay, but also for the external quasi-basin. To make matters worse, the entrance of the Duncan Dock lies well within the middle ventral loop or antinode of the binodal oscillation outside, and the disturbance is therefore very readily transmitted to the water mass inside the dock, which responds with a sympathetic uninodal seiche.

Nor is this the end to this unfortunate set of circumstances, for the quinqui- and sextinodal seiches outside the dock (1.95-1.70, 1.65-1.50 minutes), which have their antinodes at or near the basin entrance, also resonate with the natural periods of transverse oscillation. By yet another quirk of mischance the designed width of the Duncan Basin in relation to its length provides critical modes of two-dimensional oscillation which are very near in periodicity to the fundamental mode of transverse oscillation. There is therefore tremendous scope for the building up of resonant transverse oscillations in the dock under the stimulus of the forced seiches.

At a time when the model was responding strongly to a 1.55 minute two-dimensional seiche, a survey of the water surface was conducted to establish the nature of this oscillation. This is portrayed in the diagrams (a) to (f) of Fig. 128. The wave-period in the model was equivalent to 1.65 minutes in nature, uncorrected for the distortional effects of the model's linear scales on the time scale. Corrected, the period corresponds to 1.55 minutes in nature.

The complicacy of the oscillation will be apparent from an inspection of the several diagrams for the half-period of the seiche. Outside the harbour the forcing seiche appears to be a combination quinqui-sexti-nodal oscillation between the breakwater and the shore. Inside the Duncan Dock it is transverse at the northern end, where the movement is strongest, and diagonal towards the southern end, where the motion is rather diffuse. The nodes, it will be seen, are not immovable, both inside and outside the harbour, and this feature is generally true of all the seiches, largely because of the phase difference of the ground-swells which enter the two channels of the bay.

It would admittedly have been very difficult in the design of the Duncan Dock to avoid creating a sounding box for the external forced seiches owing to the density of their occurrence in the periodic sequence of (43). But this is largely the inheritance of a wrongly-placed breakwater (p. 279). Had all these facts been known, however, even in the face of this bad legacy, when the layout of the Duncan Dock was planned, it might have been possible by judicious variation of dimensions to avoid critical resonant conditions and so have prevented the worst featuresof Range-action.

It is, of course, not only the fundamental oscillations longitudinally and transversely that are generated in the Duncan Basin, although these are the strongest. The higher-frequency external seiches also propagate themselves internally, aided by a considerable degree of concurrence between their periods and the natural periods of the basin in the higher modes of oscillation. The binodal transverse seiche is particularly important in this respect, for as we shall later show, it is probably more disturbing to shipping than its uninodal overtone.

In the Victoria Basin the mechanism of the action follows the same pattern as for the Duncan Dock. Here there are more compartments to sustain particular periodicities of oscillation, but the highest-frequency ground-swells are not of the same consequence in the immediate lee of the breakwater owing to the damping of their amplitudes. Table IV (p. 257) will serve to illustrate this point, for the frequencies below 1.60 minutes on November 6, 1944, are noticeably absent from the breakwater-bight, although they are strongly in evidence at the opposite shore.

As the breakwater-bight constitutes a ventral loop or antinode for most of the seiches of the breakwater-shore system, the Victoria and Alfred Basins are much imposed upon by the lower frequencies. Seiches of more than 3 minutes period in the Alfred Basin, and more than 4 minutes period in the Victoria Basin, cause a pumping action or universal rise and fall of wat over the entire area of the dock (p. 300), and very strong surg through the basin entrances are characteristic of this action (pp. 26, 68, 148). The equivalent effect is produced in the Duncan Basin by all seiches exceeding a period of about 11 minutes, notably the strong seiches for the bay of 17-23 and 26-33 minutes periodicity.

To complete this summary there remains to refer to the powerful denuding action of seiches. Wherever the nodes of seiches run into shallow water, as they inevitable tend to do at intervals on shoaling beaches, extremely powerful surges may be expected, capable of transporting bed material of considerable weight and volume (p. 302). Especially will this be true of seiches of large amplitude which are resonant for some inlet, cove, submarine trough or submerged valley along a coast. Many an unwary bather has been swept to his doom by the treacherous currents of these nodal points, in coves and creeks and even along open coasts.

The author ventures to assert that the so-called 'riptides' of straight beaches are merely evidence of coastal seiches with incident nodes. Wherever a node intersects the shore, perhaps normally, but more probably obliquely, the beach slope will be found to be levelled and the sea to have cut a convex frontage into the land (Figs. 79). Wherever the seiche is antinodal, the beach levels will be higher and will appear as blunt promontories jutting into the sea. This scalloping of beaches may be observed along almost any sandy coastline where the beach material is transportable.

At Cape Town where the Eastern Mole is at right-angles to the shore we find the Paarden Eiland beach at the root of the Mole relatively unaffected by the erosive tendencies of the seiches. This is undoubtedly because the numerous seiches are all antinodal at this point and scouring tendencies are mild. The same sort of thing occurs at Margate on the south coast of Natal where the safest bathing is to be found in the immediate lee or re-entrant angle of the rocky headland which flanks the beach on the south side. Yet another example of this is found at the Riviera beach near Hermanus where all bathing is extremely dangerous except in the right-angled corner where the rock-bound coast meets the crescent line of the beach.

PART V.

THE TREATMEMT OF RANGE ACTION

> "It would seem, therefore, that by carefully observing certain (stated) precautions the method of model investigation may now be applied with confidence to practical problems".
>
> —— Report of a Committee of the British Association for the Advancement of Science, (1891)*.

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* Sir James N. Douglass, Prof. Osborne Reynolds, Prof. W. C. Unwin, Mr. W. Topley, Sir E. Leader Williams, Sir William Shelford, Dr. G. F. Deacon, Mr. A. R. Hunt, Mr. W. H. Wheeler, Sir William Anderson, and Mr. H. Bamford.

CHAPTER XIV

THE DESIGN OF AN ENGINEERING MODEL.

> "Suppose two similar systems of bodies consisting of an equal number of particles, and let the correspondent particles be similar and proportional, each in one system to each in the other, and have a like situation among themselves and the same given ratio of density to each other; and let them begin to move among themselves in proportional times, and with like motions (that is, those in one system among one another, and those in the other system among one another). And if the particles that are in the same system do not touch one another, except in the moments of reflection; nor attract, nor repel each other, except with accelerative forces that are as the diameters of the correspondent particles inversely, and the squares of the velocities directly, I say that the particles of those systems will continue to move among themselves with like motions and in proportional times".
>
> ——— Isaac Newton,
> Principia Mathematica,
> Book II, (1686).

104. The Scope of a Range-Action Model of Table Bay Harbour.

It is necessary to return now to the early stages of the researches on the Range phenomenon, when in the crisis of the war, the author was faced with the task of proceeding at once with the design and construction of a model.

The author's approach to the problem was referred to briefly in Section 21 (pp. 65-66). This fortunately gave him an insight into the fundamental nature of the problem, and its early recognition in this way unquestionably enabled many pitfalls to be avoided.

As recorded in Section 42 (p. 125), the author had the benefit of inspecting the Range-action model of Table Bay harbour constructed by Mr. George Stewart at the University of Cape Town, of seeing it in action and of assessing its shortcomings, which were many. The study of Darwin's book on 'The Tides' had by then convinced the author that the seiches of

Table Bay as a whole were intimately bound up with the oscillations in the harbour basins, and that any restricted model, such as Stewart's, which made no allowance for the seiches of the bay and introduced artificial sea-boundaries in close proximity to the harbour, could lead to entirely spurious deductions.

The author therefore planned a model which would encompass the whole of Table Bay. To ensure a reasonable size of model harbour, without making the bay too expansive, it was decided to adopt a horizontal scale of 1 inch to 100 feet or 1/1200. For this a floor space 52 x 41 feet was allotted, and in this the model lay-out was accommodated as shown in Fig. 129.

The general idea at this stage was that the model should be capable of reproducing, by means of wave-paddles across the two entrance channels of the bay, the effects of ground-swells entering the bay and forming standing waves or seiches in the vicinity of the harbour. The early studies referred to in Section 21 (p. 63) had revealed the existence of 11 and 5½-minute oscillations in the harbour, and the model was therefore designed with the emphasis on waves whose wave-length would be great compared with the depth of water in which they would be propagated. As will be seen later, this limited the usefulness of the model in the study of high-frequency wave effects or ground-swells of less than 1 minute periodicity. This was perhaps unfortunate, because the subsequent researches showed the importance of the higher frequency oscillations in their effects upon shipping: at the same time it was unavoidable without planning a model on a very much more ambitious scale.

In the light of the subsequent investigations and experiments, there is something to be said for having had a small ancillary model for the separate study of high-frequency waves which do not fall in the ground-swell category. Such a model, however, would be dependent upon the correct reproduction of the high frequency seiches in the breakwater-shore oscillating system, which might be difficult to simulate by any other means, ultimately, than by the free play of the waves in the bowl of Table Bay.

105. The Conditions of Dynamical Similarity for the Model[*].

As the model was designed for the specific purpose of reproducing the wave-phenomena of the prototype bay and harbour, some consideration of the principles of similitude as affecting this issue is necessary here.

A correct reproduction of natural phenomena on a model scale requires that the model should be dynamically similar to the prototype. Such a relationship demands that the model shall not only be geometrically similar to the prototype, but shall continue to remain so throughout such respective motions as may take place.

The model will be geometrically similar if corresponding slopes at corresponding points are identical: it will be dynamically similar if corresponding forces in the model and archetype bear a fixed ratio and are similarly situated and similarly directed.

If s, d, t, c, m and f are respectively dimensions of horizontal and vertical distance, time, velocity, mass and force in the model system, while S, D, T, C, M and F are the corresponding dimensions in the archetype; and if the dimensional ratios are respectively:

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[*] The following works were specifically consulted from the very extensive bibliography available: Levy, 'Principles of Dynamical Similarity', Glasebrook's Dictionary of Applied Physics, (London), 1922, [104], Vol.I, pp. 81-96; Hankins, 'Experimental Fluid Dynamics applied to Engineering Practice', Engg. Feb., 1944, [105], pp. 158, 177; Gibson, 'Tidal and River Models', J. Inst. C.E., Vol. 3, 1935-6, [106], pp. 699-722; Stanton, 'Engineering Research', Proc. I.C.E., Vol.232, 1930-31, [107], pp. 386- ; Groat, 'Theory of Similarity and Models', Trans., ASCE, Vol. 96, 1932, [108], pp. 273-386; also articles in 'Hydraulic Laboratory Practice', ASME, (New York) 1929, [109], pp. 759-827.

$$\left.\begin{array}{ll} \text{(i)} & s/S = \sigma, \\ \text{(ii)} & d/D = \delta, \\ \text{(iii)} & t/T = \tau, \\ \text{(iv)} & c/C = \gamma, \\ \text{(v)} & m/M = \mu, \\ \text{(vi)} & f/F = \varsigma, \end{array}\right\} \qquad (44$$

then between the moving forces and the accelerations of the model there will be relationships, for horizontal and vertical motion respectively, of the form

$$m.\frac{\partial^2 s}{\partial t^2} = f \; ; \qquad m.\frac{\partial^2 d}{\partial t^2} = f$$

and of the full-scale regime

$$M.\frac{\partial^2 S}{\partial T^2} = F \; ; \qquad M.\frac{\partial^2 D}{\partial T^2} = F$$

By the use of equations (44), the model equations of motion may be expressed as

$$\left(\frac{\mu.\sigma}{\tau^2}\right). M\frac{\partial^2 S}{\partial T^2} = F.(\varsigma)$$

$$\left(\frac{\mu.\delta}{\tau^2}\right). M.\frac{\partial^2 D}{\partial T^2} = F.(\varsigma)$$

The motions in the model will then be identical with the motions in the prototype, if

(i) $\tau^2 = \left(\frac{\mu}{\varsigma}\right).\sigma$

(ii) $\tau^2 = \left(\frac{\mu}{\varsigma}\right).\delta$

Since the wave motions with which we are concerned involve only gravity forces, effects of viscosity being unimportant, $\varsigma = \mu$, and the condition that the motions are dynamically similar is therefore:

$$\tau^2 = \sigma \; (= \delta) \qquad (45)$$

If we compare the two systems at corresponding speeds, we have, from energy considerations, relationships in the model of the form

$$f.s = \frac{1}{2} m.c^2$$

and in the prototype

$$F.S = \tfrac{1}{2} M.C^2$$

and by using equations (44), these relationships can be shown to be identical when

$$\Upsilon^2 = \sigma \ (=\delta) \qquad \text{—————————} (46)$$

Equations (45) and (46) give the time and velocity scales, in terms of the linear scales of the model, as the necessary conditions for the fulfilment of dynamical and geometrical similarity. Either of these equations by itself would really be sufficient to express the condition, for they are transmutable with the aid of (i), (ii) and (iii) of equations (44).

Now, the velocity of a gravity wave in the model or in nature is given by equation (1), (p. 107). Using its variant (4) and squaring, we have for the model

$$c^2 = (g/q).\tanh qd$$

and for the prototype

$$C^2 = (g/Q).\tanh QD$$

where q and Q are given by equation (3), (p. 107), as applying to the two systems. Since $q/Q = 1/\sigma$, and $d/D = \delta$, the ratio of velocities, squared, becomes

$$\left(\frac{c}{C}\right)^2 = \Upsilon^2 = \sigma.\frac{\tanh QD(\delta/\sigma)}{\tanh QD} \qquad \text{—————————} (47)$$

It is very clear from equations (45), (46) and (47) that perfect dynamical similarity between model and prototype in wave-phenomena will be possible only if there is perfect geometric similarity, for which the horizontal and vertical linear scale ratios σ and δ must be equal.

Using equation (5), (p. 107), as applicable to model and archetype, equation (47) may be resolved into

$$\tau^2 = \sigma.\frac{\tanh QD}{\tanh QD(\delta/\sigma)} \quad , \qquad \text{—————————} (48)$$

which, of course, again only satisfies (45) if $\sigma = \delta$.[*]

106. The Choice of Scales for the Model.

As already mentioned, the horizontal linear scale of the model, $\sigma = 1/1200$, was conditioned by the available floor space, the size of Table Bay and the necessity for having a model harbour of reasonable size for the detailed experiments that would be necessary within it.

The adoption of the same scale in the vertical direction, as required for perfect dynamical similarity, would have given a depth of water in the model harbour of less than half-an-inch, which would have been wholly inadequate for any useful purpose. The introduction of some degree of distortion in the model to gain sufficient working depth of water, was therefore unavoidable.

One of the factors influencing the choice of the vertical scale was the method to be used in the measurement of the wave disturbances in the model basins, which, as will be seen in due course, involved the immersion of small air-cylinders of a height of 1½ ins. Yet another factor was the resulting value of the nominal time-scale.

Provided the wave-length of the waves in the model is sufficiently large compared with the depths to justify the approximation that $\tanh QD(\delta/\sigma) = QD(\delta/\sigma)$, equation (48) reduces to

$$\tau^2 = \sigma\left(\frac{\sigma}{\delta}\right) \qquad (49)$$

and the nominal time-scale is $\tau = \dfrac{1}{1200.\sqrt{\delta}}$.

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[*] To overcome some of the disadvantages inherent in wave-action models with different horizontal and vertical scales, the Chief Civil Engineer, Mr. J. S. deV. von Willich, subsequently made the rather ingenious suggestion that the horizontal and vertical scales, σ and δ, should be distorted or made variable in order to make the right-hand side of equation (48) a constant quantity. This would eliminate distortion of the time-scale, although it would fail to satisfy equation (47). Up to the present no practical implementation has been given to the idea.

A little consideration will show that the selection of a vertical scale of 1 inch to 12 feet or $\delta = 1/144$ was almost automatic to ensure a convenient nominal time-scale of $\tau = 1/100$. A time-scale of 1/80 would have made $\delta = 1/225$ or 1 inch to $18\frac{3}{4}$ feet, which would have given less than 2 ins. of water for a 36 ft. depth in the prototype harbour. Any larger time-scale would have made the position worse; any lesser time-scale up to 1/100 would have yielded an awkward vertical scale, while any time-scale smaller than 1/100 would merely have increased the distortion.

The waiving of the principles of similitude by distorting the model in this way may seem to be the very antithesis of sound model-technique, yet it is often, of necessity, resorted to and frequently found to be of less consequence than might have been expected, provided suitable precautions are taken. The nominal distortion may be considered to be the ratio $\left(\frac{\delta}{\tau}\right)$. Table XII gives some record of the coefficients of distortion in several well-known tidal and wave-action models in comparison with the Cape Town model.

Table XII: Coefficients of Distortion of Tidal and Wave-Action Models.

Author or Laboratory *	Model		Adopted Scales		Coefft. of Distortn.
	Feature Modelled	Type	Horizonl. $1/\sigma$	Vertical $1/\delta$	δ/σ
a) Osborne Reynolds	Mersey River (1885)	Tidal	31,800 10,600	960 396	33 27
b) Vernon Harcourt	Seine Estuary (1886)	Tidal	40,000	400	100
	Mersey Estuary	Tidal	30,000	500	60
c) Gibson	Severn Estuary (1926)	Tidal	8,500 8,500	100 200	85 42
d) Mc.Clure	Bombay Harbour	Tidal	7,296	96	76
e) Elsden	Rangoon Harbour	Tidal	8,060	192	42
f) Allen	Mersey Estuary (1930)	Tidal	800 7,040	120 190	7 37
g) Allen	Dee Estuary	Tidal	5,000 40,000	200 400	25 100
h) Allen	Bridgwater Bay & River Parrett	Tidal	3,000	260	12
k) Netherlands Hydraulic Laby., Delft	Leith Harbour, Firth of Forth	Wave Action	180	180	1
l) Barrillon	Tamatave Harbour, Madagascar (1936)	Range Action	500	100	5
m) Hydraulic Laby., Calif. Inst. Tech.	Los Angeles Harbr. California, (1944)	Range Action	1,800 480	300 240	6 2
n) U.S. Waterways Experiment Statn. Vicksburg.	Monterey Harbour, California, (1947)	Range Action	100	100	1
o) Range Laboratory, Cape Town	Table Bay Harbour (1943)	Range Action	1,200	144	8

* a) 'On Certain Laws relating to the Regime of Rivers and Estuaries, etc.' Papers on Mechanical and Physical Subjects, (Cambridge), 1901, [110], Vol. II, p.326.

b) 'Principles of Training Rivers through Tidal Estuaries', Proc. Roy. Soc., Vol.45, 1888-9, [111], pp.504-524.

c) 'Construction and Operation of Severn Tidal Model', (London), 1933, [112]

d) 'Bombay Harbour Survey and Tidal Model', Proc. Inst. C.E., Vol.232, 1932, [113], p.66.

e) 'Investigation of the Outer Approach Channels to the Port of Rangoon by Means of a Tidal Model', Jnl. Inst. C.E., June, 1939, [114], p.3.

fgh) 'Scale Models in Hydraulic Engineering', (London), 1947, [115], pp. 246-284.

k) Cf. Allen, (ibid.), [115], pp. 304-308.

l) L.c. (ante p.154), [76].

m) 'Wave and Surge Study for the Naval Operating Base, Terminal Island, California, (Calif. Inst. of Tech., Pasadena), Jan., 1945, [116].

m) 'Wave and Surge Action, Monterey Harbour, Monterey, California', Tech. Memo. No.2-301, (Waterways Experiment Station, Vicksburg), Sept., 1949, [117].

There are noticeable differences in Table XII between the coefficients of distortion that have been used in tidal and wave-action models. Tidal models, of course, are wave-action models in an extreme sense, since tides are waves of great length, and they are usually constructed for the purpose of studying the effects of tidal currents on scour and siltation. Wave-action models are usually concerned more with the measurement of wave-heights and critical frequencies. But the coefficients of distortion given in Table XII are perhaps not a true reflection on the actual degree of distortion in the models as far as the interpretations of velocity and time are concerned To understand the position better, we shall need to consider a few simple examples.

107. The Effective Distortion of the Model.

On the basis that the wave-lengths of the waves in the model are always great compared with the depth of water in which they propagate, equation (47) approximates to

$$\gamma^2 = \sigma(\delta/\sigma) \qquad (50)$$

which in respect of all horizontal motions in the model represents a distortion of (δ/σ) from condition (46) for perfect dynamical similarity. The factors of distortion in equations (49) and (50), however, refer to the use of a time scale of $\tau=\sqrt{\sigma}$ and a velocity scale of $\gamma=\sqrt{\sigma}$, whereas in actual practice we employ the time and velocity scales given by (49) and (50) in toto.

Thus in the case of the Table Bay Harbour model the true distortions of time and velocity measurements will be relative to the respective scales of 1/100 and 1/12 adopted for these quantities and not to the scales of 1/34.63 for each, that would apply if the model had a uniform linear scale of

$\sigma = \delta = 1/1200$.

We have then to enquire what the effects of this distortion will be on the interpretation of wave-phenomena when using the adopted scales (49) and (50), as compared with the correct wave-phenomena that would be reproduced in a perfect model.

To crystallise our ideas on this subject, we may consider the fundamental longitudinal oscillations in two models of a prototype rectangular basin, 6000 ft. long and of a uniform depth of 48 ft. Model A, built to the scales $\sigma = 1/1200$ and $\delta = 1/144$, is distorted; model B, to a uniform linear scale $\sigma = \delta = 1/1200$, is dynamically similar to the prototype. Both model basins would be 5 feet long, but A would contain water 4 ins. deep as against only 0.48 inch for B.

If we disregard any surface tension, frictional effects or other complications that might arise in model B because of its very shallow depth of water, we may calculate the periods of the fundamental seiches in each model-basin as they are likely to be found experimentally from equation (18), (p. 237). Thus basin A will oscillate in resonance with a period of 3.053 seconds; basin B with a period of 8.815 seconds. As the time scale of A is 1/100, while that of B is 1/34.63, each model records a critical periodicity in nature of 5.09 minutes, which is the natural period of the prototype basin. Despite its distortion, therefore, model A has proved itself the equal in efficiency of model B, and the effective distortion of time-events is nil. There is a necessary qualification to this result, however, in that the distortion is nil only so long as the length of the model basin A is large compared with its depth of water.

The mechanism of how this rather surprising result has come about may be better understood in generalised terms. Any time event in a model involving wave-motion can be represented by the equation

$$t = \frac{s}{c} = \frac{s}{\sqrt{(g/q)\tanh qd}}$$

$$= \frac{S.\sigma}{\sqrt{\sigma(g/Q)\tanh QD(\delta/\sigma)}} \qquad \text{———— (51)}$$

which can be considered to apply to Model A for any type of wave of velocity c, given by equation (4), (p. 107). Model B, which is dynamically similar to the prototype, for which $\sigma = \delta$, will record the same time events, as

$$t = \frac{S.\sigma}{\sqrt{\sigma(g/Q)\tanh QD}} \qquad \text{———— (52)}$$

To obtain the equivalent time of the event in nature, result (51) for model A must be divided by its time-scale, $\frac{\sigma}{\sqrt{\delta}}$. Similarly, (52) must be divided by the time-scale for model B, namely, $\sqrt{\sigma}$. Performing this operation, and denoting T_A and T_B as the equivalent times in nature, we obtain:

$$T_A = \frac{S\sqrt{\delta}}{\sqrt{\sigma\cdot(g/Q)\tanh QD(\delta/\sigma)}} \qquad \text{———— (53)}$$

and

$$T_B = \frac{S}{\sqrt{(g/Q)\tanh QD}} = \frac{S}{C} \qquad \text{———— (54)}$$

The undistorted model B gives the result we desire, the true time of the event in nature. Model A will only give us the same result so long as the hyperbolic tangent in the denominator of (53) is small enough to justify the approximation that it may be replaced by $QD(\delta/\sigma)$, and this only happens when the wave-length of waves in the model is large compared with the depth. For then, in both cases, (53) and (54) reduce to

$$T_A = T_B = \frac{S}{\sqrt{gD}} = \frac{S}{C}$$

and the distortion of model A is nil, as we found it in the numerical example.

In order to make the distorted model A give true results in all circumstances a factor of correction must be applied to the experimental results as interpreted by the nominal time-scale, $\sigma/\sqrt{\delta}$. Thus (53) will be identical with (54) if we correct it by the factor

$$\theta = \frac{T_B}{T_A} = \sqrt{\frac{\sigma.\tanh QD(\delta/\sigma)}{\delta \tanh QD}} \qquad \text{\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_(55)}$$

The inverse of (55) gives the ratio of the model times (converted to natural conditions by use of the nominal time-scale) to the true natural times. Thus, if T_m and T_n are respectively the prototype times in the model and in nature, and, for convenience, QD and δ/σ are written

$$\left.\begin{array}{ll} \text{(i)} & QD = \alpha \\ \text{(ii)} & \delta/\sigma = \phi \end{array}\right\} \qquad \text{\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_(56)}$$

$$\frac{T_m}{T_n} = \sqrt{\frac{\phi.\tanh\alpha}{\tanh\alpha\phi}}$$ [*]

$$= \sqrt{1 + \frac{\alpha^2}{3}(\phi^2 - 1)}$$

approximately._____(57)

The true measure of distortion is now discernible from equation (57); being the extent to which the quantity under the root-sign exceeds unity. The importance of keeping ϕ , the nominal coefficient of distortion, as low as possible in wave-action models is now apparent, and we see also why it is permissible to allow so much larger coefficients of distortion in tidal models, since α for the latter is so much smaller a quantity.

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[*] Accurate numerical calculations and graphs of corrections for the Table Bay Harbour model, based on this equation, were made by the author's assistant, Mr. W. C. [illegible]. Joosting, as an original contribution to the research. The discussion of distortional effects, here given, is, however, the author's own.
The same result has also been given by Carlotti, 'Contribution a l'etude de la Houle au voisinage des cotes', LaHouille Blanche, Nov.-Dec., 1947 [127], pp. 469-480.

The effects of the distortion upon the measurement of velocities in the model may be analysed in a similar way, but has not here been undertaken, because no quantitative measurements of velocities were made in the model or prototype (cf. Section 26, p. 77).

The extent of the distortion of time-events in the model of Table Bay, for the adopted scales of $\sigma = 1/1200$ and $\delta = 1/144$, may be visualised in a diagram of the type of Fig. 27. Thus Fig. 130 gives an enlargement of that portion of Fig. 27 that is applicable to the model, having regard to the fact that the maximum depth of sea-bed in the area modelled was 120 feet.

In the depths of water in the prototype Table Bay, all waves of periods from 10 minutes down to 30 seconds are ground-swells, and are represented by straight lines such as AB in Fig. 130, which correspond to the periodicity-lines in the shaded zone of Fig. 27. The effect of the model distortion, however, is to make the corresponding waves in the model imperfect ground-swells, or ground-swells in which there is not the same uniformity of horizontal movement of the water-particles from the free surface to the model-bed. The net result is therefore a displacement to the left of the diagonal lines of Fig. 27, which give the ratios of bottom-to-surface horizontal movement, as shown in Fig. 130. The periodicity-lines for the model are correspondingly shifted and appear in Fig. 130 as dash-lines such as DC. The extent to which these lines then deviate from their equivalents in nature, reflects the true distortion of the model.

As may be seen from Fig. 130, the distortion of the model is negligible for long-period waves, but increases progressively as the periodicity decreases, being quite considerable in deep water for waves of 30 seconds period. The shaded or stippled portion ABCD of the diagram, however, represents the actual zone of experimentation in which the model was mainly used. Surface-tension was found to play a large part in preventing the satisfactory propagation of waves of periods less than about 1 minute, and high-frequency wave-effects were therefore not studied; hence the lower limit of the experimental zone DC. Waves of periods much in excess of 10 minutes could also not be reproduced satisfactorily because of the limitations of the paddle-machinery in providing sufficient amplitude for their proper development: AB thus corresponds to this upper limitation. The remaining boundary BC of the experimental zone defines the limit of depth of water in which experiments were made in the vicinity of the model harbour. Within the zone of experimentation ABCD, therefore, it will be seen that the distortion was not critical, and the truth of this, we believe, is reflected in the excellent correspondence between model results and the measurements of the natural phenomenon, as given in the last two chapters.

108. Design of the Wave-Paddles.

One of the first considerations in the design of the model concerned the type of wave-paddles to be used.

It will be evident from Fig. 130 that the ratio of bottom-to-surface horizontal movement in the waves with which the model was ultimately tested varies from 1.0 to about 0.5 for wave-periods from 10 minutes to 1 minute respectively. The desirability of imparting corresponding horizontal movements to the water at surface and bottom via the wave-paddles largely influenced the author to consider vertical paddles of the push type, such as had been used by Bagnold* in his experiments on wave pressures, and by the Netherlands Hydraulic

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* 'Interim Report on Wave Pressure Research', Jnl. Inst. C.E., June, 1939, [118], pp. 202-226.

Laboratory at Delft for its study of wave-action in Leith harbour, Scotland.[*]

In both these cases the paddle-boards were mounted on rollers at their base and were held erect or at the desired inclination by two hinged links connecting with eccentrics or oscillating levers[†]. A somewhat similar arrangement was planned on paper in the first instance for the Cape Town model, but the magnitude of the calculated load imposed on the driving machinery through the mere necessity of holding the paddle erect by its connecting links, led the author to modify the arrangement to that shown in Fig. 131. Here it should be explained that the author had at this stage visualised employing a disc, ball and roller type of speed-control in the power-drive to the wave-paddles, on which device it was desirable to keep the load as low as possible.

The wave-boards were designed in sections 6 feet long by 20 ins. wide or deep, for suspension by end-trunnions on triangular bearing plates, forming part of over-head-supported paddle-carriages. The latter were mounted on flanged wheels, which rested in turn on the bottom flanges of Tee-rails, forming part of the main paddle-frames. Links connected the top-centre of each wave-board and the centre of each supporting carriage with opposite ends of a crank mounted on a driving shaft, which extended the full length of the paddle frame. This shaft,was connected by separate crank and connecting-rod with the driving eccentric, and was given in consequence an oscillating to-and-fro motion which varied in magnitude with

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[*] 'Report on Model Researches for Leith Harbour'; cf. Allen, (l.c. ante p. 322), [115], p. 308. Copy of the Report was made available to the author through the courtesy of the Hollandse Aanneming Maatskappij, S.A. (Eiendoms), Beperk.

[†] This type seemed more desirable for reproduction of ground-swells than wave-generators of the plunger-type, even though the comparative experiments of the Beach Erosion Board, Washington, D.C., on different types favoured a sloping-faced plunger for high-frequency wave production. Cf. Brown, 'Studies of Beach Erosion', E.N.R., Vol. 120, Feb., 1938 [119], p. 299.

the degree of eccentricity adopted. The general arrangement is clearly visible in the photographs of the completed paddles of the model, (Figs. 132 to 134).

In this assembly the oscillations of the driving shaft are imparted to the wave-boards both as a translation (via the paddle-carriages) and a rotation about their centres of gravity. The resultant movement of a paddle-board is therefore equivalent to a rotation about some other axis than its axis of suspension. By suitably varying the lengths of the links, in relation to each other, and of the crank-arms, the effective axis of rotation of the wave-board may be made to lie above or below the actual axis of suspension. In addition, the arrangement permitted of a paddle being given either a pure push-pull motion of translation, or a pure rotation about its trunnions.

With a view to reducing the overall size and expense of the model the paddles were originally designed as fixtures in the entrance-channels (Fig. 131), their direction having been determined in accordance with the shape of the coastline of the bay and the shape of the sea-bed. Substantially these directions were at right angles to the axes of the natural channels between Robben Island and the mainland. On the authorisation of the Chief Civil Engineer*, however, provision was subsequently made, before the model was constructed, for paddles which could be slewed to allow for an alteration of wave-direction.

As a result of the graphical studies of wave propagation, featured in Figs. 101 to 107, it was found possible to accommodate almost any direction of approach of swell from the outer ocean by a 15° angular variation either way from a mean line joining Mouille Point on the mainland with the south-west

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* Mr. J. S. de V. von Willich.

corner of Robben Island, for the west channel, and a similar variation either way from a mean line drawn from the south-east corner of Robben Island in a direction 60° west of north, for the north channel.

This degree of slew was accordingly provided for the wave-paddles by mounting the mechanism already described on paddle-frames (Fig. 135), which were carried on flanged wheels, running on curved rails and centred by pivots at the re-entrant angles of the boundary walls of the paddle-wells, (Fig. 129). The arrangement is clearly portrayed in Figs. 132 to 134. As may be seen from the latter photographs, the west-channel paddle comprised four sections of wave-boards, and the north-channel paddle, three. The individual sections were all identical and could be mass-produced for ultimate mounting on the paddle frames, a feature which saved much time in construction and assembly. A further advantage of designing the wave-boards in sections was the variable adjustment it permitted along the length of the paddle. Thus, the movement of the end-sections could be made smaller than that of the central sections to accord with the weaker swell-movements arising from wave refraction in the shallower portions of the entrance channels, near Robben Island and the mainland.

109. The Paddle-Driving Mechanism.

The idea of developing a mechanical device of the disc, ball and roller type for speed-control of the wave paddles arose from a study of a book on mechanisms*, which was prompted by the desire to obtain some simple method of regulating the periodicity of the paddles with the widest possible range of speed. This particular mechanism offered sensitive control

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* Jones, 'Ingenious Mechanisms for Designers and Inventors', (New York), 1935, [120], Vol. I, pp. 348-9.

over a range of speeds from absolute zero to a designed maximum and seemed eminently suitable for the purpose if it could be applied to transmit the requisite amount of power. Despite the diffidence expressed by a number of people in the ability of a point-contact frictional transmission to operate large wave paddles against a fair water resistance, the author was confident that the device could be made to work. He therefore designed the transmission shown in Fig. 136, for an ultimate power capacity of about 2 HP.

This device combined an adjustable eccentric with the speed-control, the former being specially designed to act as a flywheel for absorbing and supplying energy against the variable load of the wave-paddle. The original intention was that this mechanism should be coupled with synchronous electric motors of about $\frac{3}{4}$ HP capacity, but during the war anything in this line was quite unprocurable, and 500-volt single-phase motors developing 1.8 HP at 1410 rpm had to be used instead.

The pulley on the disc-shaft of the speed-control was connected by V-belting to reduction gearing, and was therefore direct driven by the motor. The movement of the disc, which remained constant, (subject only to minor fluctuations in the speed of the motor) was communicated to the roller through the medium of the steel balls, whose position could be varied to increase or diminish the radius of contact on the disc. A hand-wheel and locking screw facilitated fine adjustment of the twin balls, and the amount of pressure, (and therefore power) transmitted by the disc to the roller was controlled by a 200 lb. capacity spring, whose compression could be regulated also by handwheel and locking screw. It will readily be seen that by suitably setting the position of the balls in relation to the disc, the speed of the roller, and therefore the driving eccentric, could be varied almost infinitesimally between zero and absolute maximum speed.

The apparatus, as finally constructed and installed, may be seen in detail in Figs. 137 and 138. Fig. 138 shows the adjustable eccentric, a feature of which was the automatic balancing of the connecting rod and crank-pin for any eccentric radius. Eccentric radius was adjusted by unlocking the clamping nut on the crank-pin and turning the screw-shaft, which may be seen in Fig. 138 lying diametrically in the plane of the flywheel. By means of opposing threads on the screw shaft, the counterweight was made to move an equal distance in or out from the flywheel centre to balance the setting of the crank-pin.

The paddle-driving machinery was mounted on a stand carried on three rollers, as shown in Fig. 139. It was coupled to the paddle-frame by means of angle ties so that the driving machinery turned about the same pivot as the frame. This ensured a fixed relationship between the machinery and the paddles for any directional setting of the paddle-frames; at the same time the paddle frames were relieved of the very heavy weight of the driving machinery.

The necessary pulley drives, countershafts and reduction gearing were all accommodated within these stands, as Fig. 140 makes clear. Fig. 141 is a photographic impression of the complete assembly of paddle-driving machinery, which may be seen also, in relation to the paddles as a whole, in Figs. 132 to 134.

The paddle-driving machinery was found in practice to be eminently suitable for the purpose for which it was designed. One particularly advantageous feature of the speed-control was that sensitivity of speed-adjustment increased with the roller-speed (or wave-frequency), owing to the retraction of the ball-carriage to increasing diameters on the disc. Two sets of gears were, nevertheless, provided, one for normal working in the range of wave-periods from 1½ minute (in nature) upwards, and the other for high-speed working. The normal disc-speed was about 30 rpm, and full retraction of the ball-carriage to a diameter of 8 ins. gave a roller speed of 80 rpm, or a period per revolution of 0.75 second, equivalent to 1¼ minutes in nature. For high-speed working the disc-speed was about 80 rpm, and the corresponding limiting periodicity was about 0.3 second, equivalent to about 0.5 minute in nature. The relationships between periodicity and disc radii are given in detail in Fig. 142.

No special difficulty was encountered in transmitting the requisite amount of power. It was actually found necessary to coat the disc, balls and roller with grease and heavy oil, and to replenish this frequently to prevent scoring of the steel balls. The disc and roller surfaces had, of course, to be of intensely hard, high-grade steel to withstand any indenting from the balls. It was found that, by careful operation, any serious grooving of the surfaces could be avoided, and local work-hardening combined with efficient lubrication no doubt prevented any serious wear.

110. Development of Autographic Dynamometer Connecting-Rods.

It is appropriate here to describe the steps that were taken to measure the amounts of power transmitted by the wave-machines. This study was necessary to arrive at the paddle settings which would give the requisite amounts of wave energy through the two entrance channels of the bay in order to correspond with nature.

An attempt was made to measure the energies accurately at the motors by the use of indicating wattmeters, but it was found that the energy needed to drive the paddle-mechanism was only about 0.4% of the energy required to drive the motor and gearing, and it was impossible to assess it accurately at all.

A manual attempt to measure the thrust through the connecting-rod fared no better. Here the connecting-rod was detached from the paddle-crank. The paddle-crank was then operated manually by pulls transmitted through two spring-balances affixed to its end and held in the hands of an operator. The maximum registered pulls on the forward and back strokes were then recorded for a whole range of speeds and length of stroke, the operator judging his speed and stroke by watching the performance of the detached driving machine. When the no-load (no water-resistance) and full-load performances were compared, however, the thrusts were so nearly the same that the amount of energy imparted to the water was not above the limits of error in assessing the thrusts.

The road out of the impasse was then found in the design of a dynamometer which could be incorporated in the connecting-rod. Figs. 143 (a) and (b) show the author's rough designs for this instrument, and Figs. 144 and 145 are photographs of the apparatus as it was finally designed and installed.

The principle of the instrument was very simple. The connecting rod now consisted of two separate pieces held in alignment by the springs-holder (Fig. 144). The end spring-plates were bolted together by tie-rods, the uppermost in Fig. 144 being screw-connected to the connecting rod, and the lowermost acting as a slide for the remaining part of the connecting rod, which was screw-connected to the central spring-plate. The latter was permitted to slide over the tie-rods, and was thus free to work either way against the compression forces of the springs. By adjusting the tie-rods to bring the springs into initial compression the central spring-plate could be made to suffer a small displacement in either push or pull relative to the end spring-plates, and this deflection was magnified by the indicating lever and scribed on the smoked drum. The drum was made to turn in proportion to the length of the stroke by the pulley-and-cord system portrayed in Fig. 143 (b) and visible in Figs. 144 and 145.

By this device the connecting rod was made to trace its own indicator diagram, (as in Fig. 144), the area of which represents the power transmitted. The extent to which the two dynamometer connecting-rods that were constructed were capable of recording the same effects may be gauged from Fig. 146, wherein the indicator diagrams traced by each, when interchanged in the west and north paddles, are compared.

111. General Features of the Model Design and Construction.

To return to the model itself, we have already noted (p. 316) the outlines of the model tank, given in Fig. 129. Generally these were determined by the shape of Table Bay and the necessity of providing wells for containing and slewing the wave-paddles.

The outer walls of the tank, of 1:2:4 concrete, 4 ins. thick and 16 ins. high, were erected first upon the concrete floor of the laboratory, provision having been made beforehand in the latter for the drainage depressions in the two paddle-wells, leading to the sub-surface sump, which was common to both.

Over the entire floor of the tank, thus created, and up the insides of these outer walls, was laid a $\frac{1}{2}$-inch layer of mastic asphalt. A 2-inch layer of 1:2:4 concrete was then superposed over this and screeded level, after which shuttering was erected for 2-ins. thick concrete innerwalls and 4-ins. deep copings to seal the asphalt lining and bring the tank walls to their final height of 1'-8" above laboratory floor-level.

At this stage the tank was checked for water-tightness, only to discover the existence of several large leaks. The specification had stipulated that the asphalt should be laid in two separate layers each 3/8-inch thick, but only one layer ½-inch thick was actually put down due to an oversight, and to this circumstance must be ascribed the inefficiency of the seal. The area of the tank floor which was subsequently to be covered with the weak concrete mixture forming the sea-bed was therefore treated with several thin coats of bituminous emulsion, after all cracks or bad joins in the concrete had been cleaned out and grouted with pitch. The floors of the paddle-wells and the sides of the tank were then coated with a solution of silicate of soda. These measures were found to be effective and, thereafter, seepage was virtually eliminated.

While waterproofing treatment was continuing, construction of the model harbour itself was begun. A level platform or shelf, 6-ins. deep, of 1:3:6 concrete was laid over that portion of the tank-floor south of the No. 34 line of abscissae (Fig. 129). Steel plates simulating breakwater and jetties, of the appropriate thicknesses and heights, were embedded in this shelf in their correct positions, and timber shuttering, previously fabricated to a full-size plan, tied in with the co-ordinate system, was erected round them (Fig. 147). The fixed portions of the model harbour, comprising the Victoria and Alfred Basins and the old foreshore were then cast in rich cement mortar.

When waterproofing treatment of the remainder of the tank-floor was complete, sheet-tin templates, cut to the profiles of the sea-bed along the lines of abscissae Nos. 1 to 33

(Fig. 129) were erected in these positions at intervals of 12 ins. apart. The templates were nailed to 1-inch square timber runners along their base and were held vertically in position by removable transverse timber spacers with saw-cuts at 12-inch centres to bite on the tin. The spaces between the parallel templates were then filled with a 1-to-8 mix of cement and coarse sand and were surfaced with a harder skin of good mortar and screeded to the profile-shape of the embedded templates.

Round the Milnerton and Blaauwberg shore the templates were all cut away to a level equivalent to about 30 feet below low water, so that the coastline could be moulded here in sand. This provision was made with the idea of watching the effects of sand-travel under wave-action and with a view to experimenting with the mouth of the Diep River, which, it will be seen from Fig. 129, was incorporated on the east side of the model. Special tin templates for moulding the sand along the shoreline were arranged to rest upon the east-side tank-walls above the sand-trough thus created. These latter templates were removable and were only placed in position when required.

The portion of the model bay south of the No. 34 line of abscissae (Fig. 129) was, as we have seen built up as a level concrete shelf 6 ins. high above tank floor-level. Upon this shelf coarse sand was placed and moulded to the shape of the sea-bed with the aid of overhead ceiling-suspended tin templates secured to light angle-bar frames, which may be seen in Figs. 132 and 133. These templates were counterweighted and could be raised or lowered with a flick of the finger on the wall-cords.

The provision of a sand bed in this area was made to facilitate the insertion and proper bedding-down of model harbour constructions such as breakwaters, moles, groynes, etc.

A solid bottom, curved to the shape of the sea-bed, would have created difficulties of fit, which is important where elimination of ground-swell penetration is being sought.

A travelling platform (Figs. 132 and 133) with flanged wheels running on I-girder rails, spanning this area (Fig. 129), provided a self-propelling deck from which objects could be lowered into position in the harbour area without disturbing the sand bed, or from which bed-moulding operations could be carried out. An operator on the platform could move himself to any desired point by pulling on tow-ropes, which passed round pulleys on the I-girder rails and were fastened to the platform (Fig. 132).

The Duncan Basin, it will be seen from Fig. 147, was mainly constructed of removable timber sections. Rapid changes in the shape of the basin by substitutions or additions could thus be effected, and the conditions existing in the prototype harbour before its construction could be reproduced by its removal. Figs. 148 (a) and (b) show the completed model harbour.

The co-ordinate system to which the model lay-out was aligned (cf. Figs. 109 and 129) was projected on to the fixed bed of the model and the tops of the tank-wall by white paint lines with the appropriate letters and numbers. These lines were visible through the water and served a very useful purpose in identifying particular points in the model in relation to their positions on the map.

The deepest portions of the model were the paddle-wells and sump (Fig. 129). The latter was situated behind Robben Island in the model and communicated with each paddle well through openings some 9 ins. wide. To prevent as far as possible the back-water effects of the paddles permeating between the two paddle-wells via the sump, the main body of the latter was cut off by baffle-walls with openings only in their base, leaving only a right-angled connecting channel between the paddle-wells. Back-water oscillations penetrating this channel tended to be thrown back on themselves at the re-entrant angle. The sump stilling basin, thus protected, was used as a water-level indicator, simple apparatus for this purpose being connected to float and counterweight as may be seen in Fig. 61. The Kymograph drum in this illustration was used as occasion demanded both for the level-indicator (on the right) and the microbarograph (on the left).

Although tides were not a feature of the Range-problem, their effects could be simulated by simple means, merely by operating the inlet and outlet valves of the water supply and drainage pipes, so that the level-indicator followed a sequence of tide-curves on the rotating kymograph drum (Fig. 61).

The supply pipe to the model divided along the two paddle-wells, and by means of perforations in the distribution pipes water was admitted in uniform quantities along their lengths. Tidal influences could thus be obtained when wanted with a minimum of artificial surging.

To prevent the back-water effects of the paddles filtering past the paddles into the model area, hinged wave-traps or baffle-plates (Fig. 149) were provided for blocking the clearances at the ends of the paddles. These clearances, of course, varied according to the orientation of the paddles, and this circumstance was allowed for by providing different angular settings for the baffle-plates. Being hinged to the side walls of the paddle-wells, the baffle plates could be folded against the walls, as necessary, or slewed outwards to form re-entrant wave-traps, locked in position by spigot-tubes pushed into holes in the tank-bottom.

112. The Measurement of Wave-Heights in the Model.

At the time that the Cape Town model was first planned and it became necessary to consider ways of recording effects within it, the world war was at a critical stage, and materials and instruments in particular were difficult to secure. The prospect of acquiring any suitable instruments from overseas appeared hopeless and no suitable instruments were procurable in South Africa, so that it became necessary to improvise with available local materials. As all electrical apparatus was in very short supply it did not appear feasible to elaborate an electrical instrument using oscillographs and other complex units.

Fortunately, the quest for a suitable instrument for the prototype harbour, leading to the design of the seichometers (cf. Section 23, p. 71), suggested a principle that might be worthy of development on a model scale. The principle had been used successfully for remote-control deep-sea tide-gauges and depended on the transmission of pressure through an air column in a pipe connecting an air-cylinder immersed in the sea with a recording fluid-manometer*.

The adaptation of the principle to an instrument suitable for precise measurements of small water-movements in a model involved many problems and considerable experimentation.

For his portable tide-gauge Honda† used a mercury-manometer, in the small limb of which a conveniently small movement of the mercury column could represent a fairly large tidal fluctuation over the air-cylinder. On a model scale, small variations of water-level could obviously not make any

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*Cf. Field and Cust's tide-recorder as developed by the Cambridge Scientific Instrument Co., Glazebrook's Dictionary of Applied Physics, (London), 1923, [121], Vol. III, p. 546. See also, Honda, 'A Portable Aero-Mercurial Tide-Gauge', Phil. Mag., Vol. X, 1905, [122], pp. 253-259.

† Ibid,[122].

sensible impression on mercury, and some other manometric fluid had to be sought. It was questionable, also, whether Honda's theory for the prototype instrument, which was applicable to gradual tidal movements, would apply to a model in which high-frequency recording was necessary.

The author was nevertheless guided by Honda's result that

$$\frac{\eta_1}{\eta_4} = \frac{a_4}{a_2} + \rho\left(1 + \frac{a_4}{a_3}\right), \quad \text{approximately.} \qquad (58)$$

where η_1 and η_4 are respectively the changes in level of the water-surface and of the fluid-meniscus in the small limb of the manometer; a_2 , a_3 and a_4 respectively the cross-sectional areas of the air-cylinder, large limb and small limb of the manometer; and ρ the density of fluid in the manometer. Transposing, (58) may be expressed as

$$\rho = \frac{(\eta_1/\eta_4 - a_4/a_2)}{(1 + a_4/a_3)} \qquad (59).$$

By aiming at making the meniscus-movement, η_4 the same as the wave-movement to be measured in the model, for which $\eta_1/\eta_4 = 1$ in equation (59), it was found that the density of the manometric fluid had to be less than unity. After improvising an experimental manometer and air-cylinder, the author made numerous experiments with various light oils and volatile fluids, and eventually found that pure paraffin with a specific gravity of about 0.88 gave an encouraging performance.

A theoretical investigation of the relationships that would prevail when the water-level over the air-cylinder performed a sinusoidal rise and fall $\eta_1 = A_1 \sin pt$ with an angular frequency $p = 2\pi/\tau$, or periodicity τ , was next undertaken and led to the results[*]:-

$$\left.\begin{aligned}
&\text{(i)}\quad p = \frac{a_1 R}{a_2 A_2}(2g)^{\frac{1}{2}}\left[A_1^2 - \left\{A_2 + \rho A_4\left(1+\frac{a_4}{a_3}\right)\right\}^2\right]^{\frac{1}{4}} \\
&\text{(ii)}\quad \frac{A_2}{A_4} = \frac{a_4}{a_2}\left\{1 + \frac{V_0 \rho g}{a_4 P_0}\left(1+\frac{a_4}{a_3}\right)\right\} \\
&\text{(iii)}\quad R = \int_0^{\frac{\pi}{2}} \sqrt{\cos\theta}\,.\,d\theta = 0{\cdot}3814.\pi^{\dagger}
\end{aligned}\right\} \text{(60)}$$

Here a_1 , a_2 . a_3 and a_4 are respectively the cross-sectional areas of the vent tube of the air-cylinder, the air-cylinder itself, the large limb and the small limb of the manometer; A_1 , A_2 . A_4, the amplitudes of vertical displacements respectively of the water-surface being measured, the water-surface in the air-cylinder, and the fluid-meniscus in the small limb of the manometer; V_0 and P_0 respectively the initial volume of air and the initial pressure of air in the air-cylinder and connecting tube to the manometer, under static conditions. As the sizes of glass tubing available for the manufacture of manometers were distinctly limited it was found necessary to select large and small bore diameters of 20 and 6 mm respectively. Further, as a result of trial experiments it was decided to adopt a vent-tube diameter of 3 mm for the air-cylinder. This left the internal diameter of the air-cylinder to be determined.

By the use of equation (58), for which η_1/η_4 was taken as unity and ρ as 0.88, the diameter of the air-cylinder, to give full-scale reproduction of wave-heights, was computed to be about 30 mm. This was the cylinder-size actually adopted, but before accepting it, check calculations were made by the

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[*] As the full derivation of these formulae is complicated and of exceptional length, it has been omitted from this work. The validity of the results may, however, be judged on the basis of the discussion here following, and in Section 114, (post).

[†] The value of this integral was obtained by graphical means.

use of equations (60) to verify that the manometer would reproduce the water-movement full-scale at all periodicities above about 1 second. At the last minute it was announced that 20-mm-bore tubing was unprocurable and 25-mm bore had to be accepted in lieu thereof. It was decided nevertheless to retain the 30 mm size of air-cylinder.

For the air-cylinder and manometer sizes adopted, (which, besides the bore-dimensions already mentioned, included lengths of 32 and 60 mm respectively), and for an assumed 30 ft. length of 6 mm-bore rubber tubing connecting the units, equations (60) resolve to

$$\tau = \frac{5{\cdot}092\,A_4}{\sqrt{A_1^2 - 1{\cdot}019\,A_4^2}} \qquad \text{\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_(61).}$$

If we consider that all the waves to be measured, (of whatever periodicity τ), have an amplitude, A_1 , of $\frac{1}{4}$ inch or 0.02 ft., the corresponding amplitude of the movement, A_4, reproduced in the small limb of the manometer by the oscillations of the meniscus of the paraffin, may be calculated from equation (61). Thus the periodicities, that will make A_4 have the successive values given in the first column of Table XIII, are:

Table XIII: Theoretical Prediction of Performance of Model Recording System.

Amplitude Manometer A_4 x 10^{-2} ft.	Periodicity τ secs.	Magnification A_4/A_1	Amplitude Manometer A_4 x 10^{-2} ft.	Periodicity τ secs.	Magnification A_4/A_1
0.2	0.09	0.1	1.2	0.65	0.6
0.4	0.18	0.2	1.4	0.81	0.7
0.6	0.28	0.3	1.6	1.02	0.8
0.8	0.39	0.4	1.8	1.37	0.9
1.0	0.51	0.5	2.0	∞	1.0

From a design point of view the magnifications at the different frequencies indicated in Table XIII were considered satisfactory. Thus a magnification of 0.6 or better was ensured for all periodicities of waves in the model above 0.65 seconds, corresponding to about 1 minute in nature. Actually, as we shall see shortly, the magnifications, as realised, were even better than these. On this theoretical and experimental basis, then, the rough design (Fig. 150) for a model recording system was evolved and put into practice.

113. The Development of the Kymatograph.

A battery of 'wave-manometers', as they came to be called, was installed in the Range laboratory in two tiers, as shown in Fig. 151, on the left-hand side of the work-bench. They were found to be particularly useful and effective in showing up the nature of the oscillations occurring outside the model harbour during operation of the wave-paddles. A whole series of small air-cylinders, embedded fairly close together in the sand bed of the model between the breakwater and the shore and connected by rubber tubing (vide Figs. 148 (a) and (b)) to the banks of manometers, could give an impression on the latter of an instantaneous profile of the water-surface along the line of the cylinders. It was easy in this way to demonstrate the existence of the uninodal and multinodal seiches in the breakwater-shore oscillating system.

This arrangement was not used other than for making general qualitative comparisons. The author felt convinced that, as in Honda's tide-gauge, the manometer fluid could be made to actuate a float and lever-system for autographic recording of the disturbances in the model, even though the available momentum for doing it was so small and the frictional effects so large. Using small detonator tubes as floats and a home-made lever system, the author succeeded in obtaining traces on a smoked drum operated by clock-work in preliminary trials. The experiments were so encouraging that the author had the rough design for a four or five lever recording instrument, shown in Fig. 152, developed and blue-printed, and the Kymatograph of Figs. 153 and 154 evolved.

The instrument may be seen to consist of an elevated stand for a clockwork-operated drum, on which scribe four lever-pens whose fulcrums are held by the columns of the instrument. Sliding on these columns below the upper deck are the manometer-holders, which may be locked on the columns in any positions by means of hand-screws. The glass manometers are rigidly held in the holders so that their small limbs are vertical beneath the ends of the levers. Small aluminium floats ride on the surface of the paraffin and actuate the levers through fine suspender-rods.

Before the Kymatograph could be turned into a useful and reliable instrument, many practical difficulties had to be overcome. The author was obliged to make his own floats from aluminium detonator-tubes, kindly supplied by the Cape Explosive Works. Various lengths of float were tried in conjunction with various types of suspender-rod, but results were disappointing until the author soldered single loops of wire round the middle of the floats so that only ring-contact was possible with the glass. It was found necessary, too, that a float should be wholly immersed in the paraffin with its top in the meniscus so that a film of paraffin could act as a lubricant round it, while the normal surface-tension of the meniscus was harnessed as a propelling force in addition to the float buoyancy.

For a time great difficulty was experienced in securely attaching the suspender-rods to the aluminium floats, but this trouble was eventually overcome. It remained a matter of some delicacy, however, to ensure that the centre-lines of the floats were always co-axial with the suspender-rods: any deflection of serious proportions was liable to tilt the float askew in the manometer limb and impede its free functioning. With careful attention to such matters, which included also occasional cleaning of the insides of the float tubes for the removal of dust, the Kymatograph was found to be a valuable and reasonably trustworthy recording instrument. Fig. 155 is a kymatogram giving four simultaneous recordings of water-surface movements at points in the model selected at random, and illustrates the oft-times beautiful effects recorded with this apparatus.

The Kymatograph could record wave-movements in any part of the model bay by the simple provision of rubber tubing long enough to reach to the farthest corners; in this respect it was particularly useful and versatile. It was necessary, of course, that all four manometers should be connected with tubing of the same length, since their sensitivity (equation (60)-(11), p. 343) is a function of the volume, V_0, of the air-column. When long-distance measurements had been completed, it was found expedient to shorten the tubing as much as possible in order to improve sensitivity for the final experiments*.

114. Performance and Calibration of the Kymatograph.

The pens of the Kymatograph scribed on smoked paper on the recording drum, which could be driven at several different speeds to suit wave-frequencies. Kymatograms, once detached, were passed rapidly through a shellac-bath and allowed to dry, their permanence being thus secured.

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* This was carried out on the Chief Civil Engineer's suggestion.

To check the sensitivity of the tracing pens at different wave-frequencies and their individual responses to movements of the same magnitude, calibration tests were undertaken as the necessary preliminaries to experiments on the model.

Two methods were adopted in undertaking this calibration in the first instance. In the first, the air-cylinder connected to one of the manometers of the Kymograph was tied to a wire, which, by being connected to the crank-pin of the eccentric of one of the paddle-driving machines via pulleys fixed to the ceiling, was caused to rise and fall over the work-bench in a simple harmonic motion of any desired amplitude and any particular frequency. A flask of water placed under the cylinder in this condition so that it was completely immersed, provided the reverse effect of water rising and falling with a sinusoidal movement over a stationary air-cylinder. The speed of the driving machine was varied over the complete range of periodicities for which the model was designed, and short records of the pen-movements for each were obtained on kymatograms after the fashion of Fig. 156.

In the second method, which was the one subsequently adopted in further calibrations, the air-cylinders of all four manometers of the Kymograph were submerged alongside of each other in a container of water, into which dangled a plunger, attached to the afore-mentioned wire from the driving machine. This displacer, in rising and falling with simple-harmonic motion, caused the water to rise and fall over the air-cylinders in equal amounts which could be simultaneously recorded by the four pens.

By either method, the actual movements of water over the air-cylinders were precisely determinable, and the magnifications of the recordings on the kymatograms were easily obtained. Time-lags or phase-differences were found by causing an electrical contact on the displacer-wire to energise a solenoid marking-pen on the Kymograph at the foot of each stroke (cf. Fig. 156).

Fig. 157 for the No. 3 pen of the Kymatograph is typical of the results obtained on analysis. It is interesting to note that the theoretical predictions of Table XIII* (p. 344) are almost exactly confirmed in the highest and the lowest frequencies, but that for periodicities between about 1 and 4 seconds the actual magnification of the system is greater than the designed. The cause of this is probably to be found in a degree of resonance of the imprisoned air between the air-cylinder and the manometer, for the theory represented by equations (60) and (61) takes no account of the inertia of the air, water and paraffin movements.

The Kymograph pens were all similar in the above respect as may be seen from Fig. 158, which is of a later calibration. On the suggestion of the Chief Civil Engineer, Mr. von Willich, that the larger vent-tubes in the air-cylinders might increase the sensitivity of the recording system at high frequencies, experiments were made with cylinders converted for the purpose. Fig. 159 for No. 3 pen is typical of the results, which show that the larger 6 and 7½ mm-bore vent-tubes, tried out, merely increased the degree of resonance by giving disproportionately large sensitivities at periods between 1 and 2 seconds. It was decided as a result not to introduce any changes in the original design.

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* Theoretical magnifications have to be doubled to allow for the 2:1 augmentation of the pen-levers of the Kymatograph.

CHAPTER XV

MODEL EXPERIMENTS ON RANGE.

> " I have called attention to these results because this method of experimenting seems to afford a ready means of investigating and determining beforehand the effects of any proposed estuary or harbour works: a means which, after what I have seen, I should feel it madness to neglect before entering upon any costly undertaking".
>
> ——— Osborne Reynolds,
> Paper on Tidal Models, (1885).

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111. Adjustment of the Paddles for Wave-Form and Expansion.

The very first problem to be resolved on completion of the building of the model was the determination of paddle settings such that the characteristics of paddle-generated waves would be in the closest possible accord with the properties to be expected of ground-swells in nature. The paddle-design had purposely been made flexible to allow of adjustment in this regard (p. 329), but the number of possible arrangements was legion and some means had to be found of defining particular settings.

Hydrodynamical theory was used as one criterion for deciding this issue. Thus by the use of equations (5), (6) and (9), (p. 107), it was possible to determine the theoretical requirements of bottom and surface horizontal displacements of water-particles in waves of different periodicities in the depths of water prevailing in the entrance channels of the bay (cf. Fig. 130 for d= 120 ft., west channel, and d= 80 ft., north-channel). The link and lever settings to give approximate corresponding ratios of bottom-to-surface horizontal movements in the stroke of the paddles were determined by trial and error with the aid of a flat cardboard model of the wave-board and paddle-carriage mechanism. Some compromise had, of course, to be made here to avoid too much alteration of settings in the normal working range of periodicities. Within the zone of experimentation depicted in Fig. 130 fixed paddle settings were adopted, but for high-frequency effects adjustments had to be made.

A second important criterion controlling the paddle-settings was wave-expansion in the model bay at the different paddle orientations. A series of tests was run, using the paddle settings arrived at in the manner just discussed, to see whether the condition of dynamical similarity that waves in model and prototype be similarly situated at corresponding times, was reasonably well complied with. The bases of comparison were the graphically determined wave-expansions in Table Bay, which in terms of the aerial-photographic check (cf. Section 85, p. 250) could be accepted as being closely akin to the true wave-expansions in the prototype bay.

The experiments were performed by operating the paddles separately, a paddle being actuated over one or two revolutions of the driving eccentric so as to induce only a single or, maybe, double wave. Two Kymograph manometers were used for charting the path taken by the wave, one being used as a fixed 'control', placed in a selected position in the model bay, and the other being moved along the line of the wave-crest at intervals. Each position located by the movable air-cylinder had to be such that the single wave, emanating from the paddle, reached both it and the control position at the same instant. Concurrence of arrival was checked by the impulses recorded on the Kymograph drum. Once the wave-crest had been plotted in this way across the model bay, the 'control' was moved to a new situation and the process repeated.

In the first tests of the north-paddle the wave directions were found to be very different from the requirements, and it was necessary not only to slew the paddle to the extreme position shown in Fig. 120, but to alter the settings so as to throw more power on to another of the wave-boards. Similar adjustments were necessary to the settings of the west-paddle when oriented in the extreme positions. Figs. 118 and 119 show the measure of agreement with the desired expansions, ultimately obtained.

Wave-expansions round the breakwater were treated in somewhat greater detail than elsewhere. To avoid error in locating the wave positions, the movable air-cylinder was moved forward and backward of its expected position in relation to the 'control' until a belt was clearly defined within which the wave must lie. The line of the wave was then finally drawn within this belt near the mean position, in such a way as to be 'commensurable' with the plotted line of the preceding and the following wave. Figs. 118 to 120 all show that the wave expansions round the breakwater tend to be spiral rather than concentric (cf. Section 93, p. 274).

The paddle settings as finally adopted to comply with the criteria of wave-form and wave-expansion are recorded in Table XIV below:

Table XIV: Link and Lever Settings for the Wave Paddles.

Wave Direction		West Paddle Settings								North Paddle Settings					
		Robben Island		Left Centre		Right Centre		Mouille Point		Blaauwberg		Centre		Robben Island	
		CL	PL	CL	PL	CL	PL	CL	PL	CL	PL	CL	PL	CL	PL
South-West	H	5	5	5	5	5	5	5	5	5	5	5	5	5	5
	R	-1⅝	-3½	-2⅞	-4	-4⅝	-5⅞	-7⅛	-9	-1⅝	-3⅛	-3¼	-4⅝	-6⅛	-7½
West-South-West	H	5	5	5	5	5	5	5	5	5	5	5	5	5	5
	R	-2¾	-4½	-5¼	-6½	-6⅛	-7½	-4⅜	-6	-1⅝	-3⅛	-3½	-5	-6⅞	-8¼
West	H	5	5	5	5	5	5	5	5	5	5	5	5	5	5
	R	-3¾	-5½	-7⅝	-9	-7⅝	-9	-1⅝	-3⅛	-1⅝	-3⅛	-3¾	-5½	-7⅝	-9
West-North-West	H	5	5	5	5	5	5	5	5	5	5	5	5	5	5
	R	-3¾	-5½	-7⅝	-9	-7⅝	-9	-1⅝	-3⅛	-1⅝	-3⅛	-3¾	-5½	-7⅝	-9

H = No. of Hole from end of Link
R = Radius on Lever (ins.)

CL = Carriage Link
PL = Paddle Link

The lever-radii given in the above table are all negative to signify that the connections are below the level of the paddle shaft;(compare Figs. 131 and 133). It will be seen that for each paddle-carriage and wave-board, forming a section of a paddle, the wave-board is given a larger stroke, in virtue of the greater radius on the lever, than the carriage. This ensures that there is a slight rotation of the wave-board over and above the pure push-pull movement given to it by the carriage. Water-particles at the free surface are thus given a somewhat greater horizontal displacement than those at the tank-bottom, thereby simulating the relative movements of the water-particles of long waves. Those wave-boards for which the lever-radii are a maximum have greater travel and exert stronger propulsions than their adjacent members. This allows for the correct refraction of the waves in traversing the shoaling ground in each channel, which slopes up towards Robben Island and the mainland.

116. Secondary and Extraneous Effects in the Model.

Once the paddle components had been correctly set, a certain amount of preliminary experimentation with the model was possible to explore the extent to which unwanted effects might be present. Artificial boundary-conditions in a model are often a potent source of influences foreign to the prototype. Such boundaries in the case of the Table Bay model were created by the paddles themselves, which tended to convert the model into an enclosed basin, rather dissimilar from the open-mouthed counterpart in the prototype.

The ways in which extraneous effects might influence the model results lay, therefore, in the possibilities of waves, returning from the coast, being reflected again at the paddles and thrown back so as to introduce secondary effects in the seiches within the harbour area; and, further, in the chance that back-water effects from the paddles, comprising oscillations peculiar to the paddle-wells, might permeate past the paddles via such small clearances as could not be sealed by the wavetraps (p. 340), and upset the natural regime.

The nature of secondary reflections at the paddles was investigated by placing air-cylinders of the Kymatograph wave-manometers immediately in front of the paddles and at the opposite shores and by operating each paddle in turn for a couple of strokes only. The wave-impulses leaving the paddles and reaching the shore were thus recorded and the time-interval between them gave a yardstick for detecting any returning waves at the paddles. It was found, as might be expected, that a reflected pulse did return to the west-paddle off the crescent-shaped coast of the bay, but that it was not above 30% of the initial wave-amplitude. No return influences could be found at the north-paddle, and the paddles individually seemed to have little effect upon each other.

It may be argued that a measure of reflection of coastwise-returning waves off the paddles is not of serious consequence, since the general effect will merely be to superimpose on the initial wave-train a second train of weaker waves of the same periodicity but with somewhat different wave-fronts. The only effect of this will be a slight tendency (and probably not a very apparent one) towards the formation of short-crested waves, which are of common occurrence in the prototype bay when superposed swells arrive from slightly different directions.

The normal clearance beneath the wave-boards in the paddle-wells was 3 ins. To test the effect of the closure of this gap and also of the small openings at the ends of the paddles and between the individual wave-boards, temporary sills and side-stops were introduced sealing off these openings. Lengths of channel-beam laid web-uppermost under the wave-boards of the paddles acted as sills, and canvas strips were used for the side-stops.

The oscillations between the breakwater and the shore for the two cases, with and without sills and side-stops, were measured at 15 different positions (Fig. 160) for a particular wave-period of 2.72 seconds or 4.6 minutes in nature. The form of the oscillation remained essentially unchanged in the two cases although there were minor differences in the registered maximum amplitudes. The profiles of the water-surface along the line of the measuring positions at the instant that the oscillations reached maximum amplitude at the shoreline-antinode are shown by the full-lines within the ventral loops in Fig. 160.

The conclusion drawn from these and other related experiments was that the fundamental characteristics of the seiches in the harbour area were not sufficiently affected to warrant the retention of the sills and side-stops, which were in any case difficult to adjust when paddle-slewing became necessary. In all subsequent experiments they were, therefore, omitted.

117. The Problem of Dual-Paddle Operation.

While the control of wave-form, direction and expansion depended on the arrangements of the component units of the paddles within the paddle-frames, the control of wave frequency and amplitude lay in the adjustment of the driving machinery, periodicity being set by the speed-control and amplitude by the eccentric radius or length of stroke imparted to the crank on the paddle-shaft.

Obviously, if the simultaneous entry into Table Bay of swells via the two entrance channels was to be correctly simulated in the model, it was necessary that the relative amounts of wave-energy introduced into the model by the paddles be proportional to the relative amounts transmitted through the channels in nature. The overall amplitude-settings or eccentric-radii on the west and north-paddle driving-machines had therefore to bear a definite relationship for each periodicity.

The problem which this posed was indeed a difficult one. It was suggested to the author by the Chief Civil Engineer that it could be entirely circumvented simply by operating the paddles independently, on the thesis that the effects of the partial seiches found for single-paddle operation must be part and parcel of the effects of the combined seiches for dual-paddle operation.

At first sight this argument seems fair enough, for if we take a case in point, that discussed in Section 93 (pp. 268-273) and Fig. 116, for an 11-minute seiche outside the harbour, it is clear that the resultant of the west and north channel effects derives from the simple addition of the component seiches. But in point of fact the essential problem is not evaded at all. Single-paddle operation permits of periodograms of critical frequencies being drawn up for the oscillations inside the harbour basins readily enough, but to obtain the true critical frequencies as in nature, it is necessary that the two periodograms for independent working of the paddles be added. The two periodograms, however, can only be added if their amplitude-scales are in the correct proportions in which wave-energy enters the two channels of the bay. Moreover, once the addition is made it will be found that, unless the periodogram peaks for single-paddle operation exactly reinforce each other, the new periodogram peaks representing the additions will be differently located. To take a simple parallel example, if we add together the positive parts of two cosine curves that are displaced by 90°, we obtain a peak amplitude 41% greater, intermediate between the original peaks.

The inherent difficulty being thus inescapable, it seemed to the author the soundest procedure to investigate the question of wave-energy entering Table Bay, derive the relative eccentric radii for the two paddles, and operate the paddles together so that the addition of effects would be performed automatically in the model itself, as in nature.

118. Dissipation of Wave-Energy with Wave-Refraction.

The problem of assessing the wave-energies carried into Table Bay by incoming swells was approached in the first instance from an experimental angle, to obtain information on the manner in which wave-energy is dissipated on expansion of waves over shelving ground.

Using the west paddle of the model alone, single waves were created whose amplitudes were measured at numerous points along the wave-fronts for different positions of the fronts in their advance towards the harbour. As in the wave-expansion experiments (p. 351), two of the Kymatograph manometers were used in this work, the air-cylinder of one being used as a 'control' and that of the other being moved along the line of the wave-crest.

A typical kymatogram obtained in these experiments is reproduced in Fig. 161. The letters and numbers therein refer to the coordinate system and define the positions successively occupied by the movable air-cylinder (cf. Figs. 162 (a) and (b)). For each such position two recordings of wave-amplitudes were made, the control being registered in every case to check uniformity of conditions. In measuring the kymatograms attention was paid only to the first crest and trough of the wave-group, since following waves were liable to be affected by the reflections of the preceding ones.

Using equation (17), (cf. Section 81, p. 236), as a measure of the wave-energy per unit width per wave-length, the products of the square of the amplitude and the square-root of the depth were plotted along the wave-crest for each frontal position of the wave, as in Figs. 163 (a) and (b). Some irregularity in these curves is to be expected but it is noticeable that the energy of the wave apparently increases near the shore when theoretically it should taper away to zero. This appears to arise from the fact that near the shore the measured amplitudes are always about double of what they should be for progressive waves, because it is impossible to dissociate a wave in such circumstances from its reflection. The correct energies for consideration near the shore are thus about one quarter of the amounts indicated by the measured amplitudes.

not been found in nature

After smoothing out irregularities in the curves of Figs.

163, the wave-energy per unit width per wave-length was plotted along the streamlines (Figs. 162) as a percentage of the energy at the initial measuring position or frontal line, with the results shown in Figs. 164 (a) and (b).

It was then argued that since curvature or refraction of the streamlines involved expansion of the wave in shallow water, and thereby automatically took account of variation of depth, it should be possible to find a single relationship connecting wave energy and cumulative refraction or curvature. Figs. 165 (a) and (b) represent the results of plotting the wave-energies for all the streamlines from the data of Figs. 164 against the angles of curvature of the streamlines. Although there is considerable scattering of plotted points, their general disposition favours a relationship of the form of a tractrix. It is interesting to note that the separate model studies for west and south-west orientations of the paddle confirm each other almost exactly in the mean relationship of wave-energy to streamline-curvature.

allen 5
11 graph [illegible]

119. Wave-Energy entering Table Bay.

The author's idea in conducting these experiments and in guiding their analysis to this result, was that, by assuming the initial wave-energy per unit width per wave-length to be 100% along an arbitrary straight line representing the frontage of a swell in the open ocean west of Table Bay, the percentages of energy per unit width per wave-length along the lines of the wave-paddles could be assessed by graphical means simply by determining the curvature suffered by the streamlines of the waves in reaching the paddle-positions. Thus, to take a specific case, Fig. 166 shows the positions of the wave-paddles, oriented as in the model for the south-west swell-direction, superposed on a chart of graphically-integrated south west ground-swells. The points numbered along the paddle-positions represent points of intersection with streamlines. By noting at, say, point number 3 along the line of the west paddle, the angle which the tangent to the streamline at that point makes with the south-west direction, namely, 13°, we may from Fig. 165 (b) assess the energy per unit width per wave-length as a percentage of that further back along the streamline where the direction was truly south-west, namely 47%. The inference here is that the wave has lost 53% of its original energy along that particular streamline through translation and refraction.

By plotting the energy-percentages per unit width along the line of the wave-paddle, the total energy per wave-length at the paddle would be given by the area under the curve, and the ratio of these areas for the west and north paddles would be representative of the relative proportions of wave-energy reaching the entrance-channels of the bay from the assumed swell direction.

An inherent deficiency in the application of the results of Figs. 165 is the implied assumption that there is no loss of wave-energy if there is no deviation of a streamline. Strenuous efforts were made to overcome this by separating the pure translation-losses of energy from the losses arising from lateral diffusion on wave-refraction in the experimental results, but without any real success. A theoretical study of the problem was then undertaken which suggested new avenues for experiment but as time was short and the author's freedom for pursuing them was unhappily restricted, it was necessary to make-do with the results already available. It was argued in justification of this that as long as the experimental relationship of Figs. 165 were applied in circumstances similar to the experimental conditions (as regards depth of water and length of wave) the results should be reasonably valid.

Fig. 167 then gives the energy-percentages along the west and the north paddles for three different swell-directions. The circumstance of these curves rising above 100% at certain points is explained by a convergence or crossing of streamlines, resulting in a concentration of wave-energy. The areas under the curves give the comparative amounts of energy reaching the west and north paddles from the different swell-directions and are recorded below in Table XV.

Table XV: Proportions of Wave-Energy entering Channels of Table Bay.

Swell Direction.	Areas under Energy Curves Fig. 167, (sq. cms)			Energy entering Table Bay as percent of maxm possible		
	West Paddle	North Paddle	Total	West Channel	North Channel	Total
N.W.	122	115	237	34(53)	30(47)	64(100)
W.	230	82	312	68(74)	24(26)	92(100)
W.S.W.	(282)	(51)	(333)	83(85)	15(15)	98(100)
S.W.	177	18	195	66(90)	7(10)	73(100)

The percentages given in the right-hand portion of Table XV were derived by plotting the total areas in the fourth column against the swell-direction*, as in Fig. 168, and relating them as percentages of the maximum found from the smooth curve drawn through the plotted points.

The interesting feature of this diagram is that the derived swell-direction which admits most energy into the bay is also the direction from which waves are found to parallel the coastline. As might be expected the importance of the north channel of the bay increases while that of the

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* The author is indebted to his assistant, Mr. W. C. Q. Joosting, for the suggestion of comparing the energies in this way.

west channel declines as swell-direction veers round to the northward.

120. The Measurement of Wave-Energy imparted by the Paddles.

In the very early stages of paddle-operation it was found, as may readily be comprehended, that unless the eccentric-radius of the driving mechanism were reduced with increase of speed, the water would at some stage begin to slop over the boundaries of the model. By a series of trial-and-error experiments adopting the criterion that vertical water-movements just outside the model-harbour should not exceed about $\frac{3}{8}$-inch, (equivalent to $4\frac{1}{2}$ feet in nature) the strokes for the paddles for different wave-periodicities were found as in Fig. 122.

Following upon the later manual efforts to measure the wave-energy imparted by the paddles, described in Section 110 (p. 334), the semi-strokes or eccentric radii for the west paddle were adjusted slightly to those shown in Fig. 123 (a), while those for the north-paddle were arbitrarily taken in the ratio of five-eighths.

When the dynamometer connecting-rods had been perfected and installed it was possible to undertake precise full-load and no-load experiments on the wave-paddles to determine the energy transmitted to the water for particular eccentric-radius settings and wave frequencies.

In these experiments careful selection of periodicities was necessary to avoid excitation of resonant back-water oscillations in the paddle wells, as these could produce undesirable effects annulling the generality of the energy measurements. For each selected period - 1.5, 2.4, 3.4, 4.5, 5.4, and 6.4 minutes (in nature) - indicator diagrams were obtained from the autographic dynamometer (Fig. 144) for different eccentric-radius settings on the driving machines with the model full and empty of water. Typical examples of these diagrams are given in Figs. 169 (a), (b) and (c), many of which were overlapped to permit of accommodation on the same chart.

From the energy diagrams thus obtained with single-paddle operation, a quantity which we may call the Energy Function, (being the area of the diagram in square inches divided by the periodicity in minutes) was determined for each, and plotted against the eccentric radius. The resulting full-load and no-load curves took the form of curves A and A_o in Fig. 170. The general pattern of these curves being obvious, it was possible to correct for inequalities by drawing the best mean continuous curves B and B_o over them. Full-load and no-load curves were in this wise obtained for each of the selected periodicities.

It was now reasonable to suppose that if, instead of keeping the period constant and varying the eccentric-radius on the machine, we had kept constant the radius and varied the speed, there would be continuity in the variation of the Energy Function with change of periodicity. In practice, of course, continuity might be disturbed by resonance conditions at a particular periodicity, but this would merely yield an embroidery on the otherwise continuous curve of the Energy Function-periodicity relationship. Accordingly, the same data were plotted in curves of the type of Fig. 171, using, however, the smoothed curves B and B_o of the series of graphs similar to Fig. 170. The curves C and C_o (Fig. 171) were obtained in this way and were then smoothed by the superposition of the best mean curves D and D_o.

The data from the series of curves D and D_0 for the different eccentric-radii were next transposed back again to the series of graphs of the type of Fig. 170 to give the circle points and a final set of curves through them, E and E_0. By this process the effects of inaccuracies of the dynamometers and vicissitudinous behaviour of the paddles was largely eliminated.

The next process of analysis involved plotting the differences ($E - E_0$) in the ordinates of the full-load and no-load curves such as E and E_0 of Fig. 170, against eccentric-radius and periodicity to give the curves of Figs. 172 (a) and (b), applicable to the west and north paddles respectively. From these graphs it was now easy to see how much energy (relatively) had been put into the water of the model by the adoption of the eccentric-radii shown in Fig. 123(a); curves W and N, of Figs. 172(a) and (b) respectively, being representative thereof.

121. Co-ordination of the Paddles to give Proportional Energies

The final stage of determining the relative paddle strokes to give the amounts of wave-energy demanded by the results of Table XV (p. 361), was now embarked upon.

The Energy-Functions of the curves W and N (Figs. 172) were re-plotted against periodicity as the dash-line curves in Fig. 173. Now, as already noted on p. 362, the criterion of adjustment for the original paddle settings had been that the west paddle should not be operated so strongly as to cause too large a range of vertical movement near the harbour nor too violent an action along the model coast. This general relationship of eccentric radius to paddle speed had worked well and there seemed no reason why it should be changed.

It was therefore merely smoothed, to obtain a more equitable energy variation, by the superposition of the curve W(W.S.W.) upon it (Fig. 173), and this new curve was then taken as the desirable maximum Energy-periodicity relationship for the west paddle to correspond with the maximum energy (83%) entering the west channel of Table Bay from the west-south-west direction (Table XV).

Since the amount of energy entering the north channel from the west-south-west direction is 15/83 of that penetrating the west channel (Table XV), the curve N(W.S.W.) in Fig. 173 whose ordinates are everywhere in the ratio of 15/83 of those of curve W(W.S.W.) will be representative of the energy entering the north channel. In a similar way, by applying the appropriate ratios of percentages in Table XV for the other swell-directions, the remaining curves of Fig. 173 were found.

The data from these several curves of Fig. 173 were next plotted on the graphs of Figs. 172(a) and (b) to give the heavy-line intercepts which define the eccentric-radii necessary to give the required distributions of wave-energy. Fig. 174 gives finally the eccentric radii for the different paddle speeds, as plotted from Figs. 172, and these settings were forthwith adopted in all the subsequent experiments on the model.

122. Speed Adjustment of the Wave-Paddles.

In any particular test simulating swells entering Table Bay from a certain direction, the paddles had to be correctly oriented, the link and lever-settings adjusted in conformity with Table XIV, and the eccentric-radii set for the periodicity in accordance with the appropriate pair of curves in Fig. 174. There remained then only to adjust the speed-control of the driving machines to obtain the required wave-frequency.

Speed adjustment was effected by moving the ball-carriage of the disc, ball and roller mechanism to and fro until the required period of revolution of the roller was reached. A stop-watch was used for timing the revolutions and fairly accurate adjustments were possible. However, it was in general impossible to ensure that the speeds of west and north paddles were exactly equal: fluctuations of line-voltage alone could throw them out of synchronism, and, once any variation appeared, the seiches at the harbour inevitably assumed the characteristics of beats in accordance with the principles described in Section 85 (p. 246).

The danger then arose that if the variation of speed between the paddles were very small, the length of the beat would become very extended, and the time involved for the completion of a full beat might far exceed the time available or allowable for a test. In such circumstances there would be no knowing in what part of the beat the test period was located, and the amplitude measurements secured might not be the maximum possible.

These dangers were avoided by making the length of the beat such that the whole beat could be recorded in the allotted time for a test. After much consideration it was found that this could be achieved satisfactorily by setting the paddles to a specific speed difference of 1% of the desired periodicity. From one to two full beats could by this device be recorded on a kymatogram and the maximum amplitude of oscillation, corresponding to a mean periodicity only ½% different from either of the paddle speeds, could always be positively identified therein.

In nature, of course, the west and north-channel groundswells arriving at the harbour from a particular direction may be expected to have a definite phase-difference, and the maximum oscillation of a beat, for which the phase-difference is nil, may be an exaggeration of the true state of affairs. However, as pointed out in Section 93 (p. 271), there will be for every periodicity up to 17 minutes at least one swell-direction for which the phase-difference of the swells in nature will be nil, and perfect synchronism can result. To be on the safe side, therefore, it was decided to ignore phase-differences and consider the maximum oscillation of the beat as the maximum effect possible at the particular frequency.

123. The Proving of the Model.

An obvious mode of testing out the reliability of the model and the principles on which its design was based was to measure the travelling times of waves over the varying depths from the paddles to the opposite coasts.

As the model had been expressly designed for long-waves it was decided to conduct experiments on waves of 4½ minutes periodicity (2.7 seconds in the model). Each wave-paddle was operated separately at this frequency for just a few revolutions at a time, sufficient to create a train of long waves. Two air-cylinders from the kymatograph were disposed at suitable points in the model bay, one near the shore, opposite the paddle, and the other at some point on the co-ordinate network remote from it, usually near the paddle or in the middle of the bay. The times of arrival of the leading wave of the group were recorded on the Kymatograph in the manner shown by Fig. 175.

The results of these tests are recorded in Table XVI, which gives for comparison the travel-times over the given distances as calculated and as derived from the graphical charting of wave-expansions (Figs. 109 and 110). The calculated times were found by plotting the reciprocal of the wave-velocity, appropriate to the depth along the streamline of the wave, against the distance between the measuring points, and integrating the area under the curve so obtained. The classical formula (equation (1), p. 107) was used for this purpose. Two calculated times are given in the table, one being applicable to nature and the other allowing for the distortional effects of the model (cf. equations (56) and (57)).

Table XVI: Comparison of Travelling Times of Waves in Model and Nature.

Swell Direction.	Paddle	Co-ords. of Points (ft.-ins.)		No. of Observations.	Travel Times (mins.)			
					Measd.	Calculd.		Graphl.
		from	to		Model	Model	Nature	Nature
West (Periodicity 4.5 mins.)	West	C-8,21-0	L-0,42-0	29	10.99	11.04	10.95	10.80
	West	G-0,22-0	Y-0,27-0	10	8.16	8.19	7.98	7.68
	North	K-0,2-0	L-0,42-0	38	19.88	19.26	18.69	18.30
	North	O-0,11-0	L-0,42-0	20	14.84	14.34	13.95	13.56
	North	R-0,20-0	L-0,41-6	12	10.79	10.41	10.26	9.13

The general agreement in the results of Table XVI must be considered very satisfactory. Not only does it prove the model reliable, but it establishes the essential applicability of the canonical equation for wave-velocity and of the degree of distortional effect at this wave-periodicity. The prototype-times determined by the graphical method, however, appear to be on the low side, to judge by the calculated equivalents. As the graphical method is also dependent on the theoretical wave-velocity in different depths of water, the discrepancy probably arises from a cumulative error in plotting.

124. The Critical Periodicities of Oscillation for the Model Harbour.

Even before the paddle settings had been determined in the way we have narrated, it was apparent that the model could successfully reproduce the Range-phenomenon at certain wave-frequencies. Preliminary explorations showed that the oscillations tended to build up when the impressed periodicity approached in value the natural period of a basin. Therefore, to seek out the dangerous frequencies whose elimination would have to be specially planned in any remedial measures for combatting Range, the first phase of model-experimenting (once the paddle-adjustments had been settled) was directed towards examining the influences of swells from different directions within a band of periodicities from 1 to 8 minutes.

The account of these experiments has been given in Section 97 (p. 283), and it is unnecessary to repeat it here, except to refer the reader to a typical kymatogram for this series of tests, reproduced in Fig. 176. Here the beat-oscillations resulting from the interaction of the west and north-paddles are clearly depicted. For the three wave-periods shown, it is interesting to note that the water is entirely undisturbed within the Alfred Basin. The figures inserted in the ventral loops of the beats give the maximum widths of the loops in millimetres.

The periodograms of critical frequencies in the harbour for the four swell-directions tested have already been presented in Figs. 124. As might be expected, a south-west swell produces the weakest response. Curiously, a west-south-west swell which admist most wave-energy into the bay, does not beget the maximum Range-effect, the blame for which must be divided between westerly and west-north-westerly swells. The reason for this is not difficult to adduce, since the latter swells, in virtue of their direction, tend to concentrate their effects more at the head of the bay.

The generally satisfactory correspondence between the critical periods for the harbour basins found in these experiments and those obtained from prototype measurements (cf. p. 286) provided further proof of the reliability of the model. Two further check experiments, however, were undertaken to endorse absolute confidence in the model.

125. Final Proof-Tests of the Model.

The model at this stage had succeeded in demonstrating Range-action and in reproducing the effects then currently being experienced in the real harbour, whose construction at that time (early 1946) was complete. It had been noted that the oscillations in the Duncan Basin had not always been the same (cf. Section 100, p. 292 and Table II, p. 134) owing to the changing configuration of this dock during its construction. It was therefore argued that, if the conditions of earlier days were reproduced in the model and the model succeeded in accounting for the observed effects at those times, the model could be relied on to expose the Range-conditions accurately for any given set of circumstances, such as might arise from alterations made to the shape or form of the harbour.

The first proof-test simulated the conditions of November, 1941, as we have described in Section 100 (p. 295). As the only observations of the natural phenomenon in 1941 were contained in the marigrams of the Lea tide-gauge at E/F berth in the Duncan Dock, it was essential that one of the air-cylinders of the Kymatograph should be located at the site of this tide-gauge in the model to record a comparative effect.

The periodograms for this experiment have already been presented in Fig. 126 (cf. p. 295). If we confine ourselves here merely to the consideration of the periodogram for the E/F berth location, we could, from the model results, expect a tide-gauge record for 1941 to show not only a critical periodicity of 4.3 minutes but also periodicities of 6.2, 6.6 and 7.1 minutes (as opposed to the normal 5.3-5.7 minute oscillations of the completed basin). The co-existence of the three longer-period oscillations would tend to show as a beat oscillation of period averaging about 6.5 minutes, which is exactly what we find in Table II (p. 134).

The second proof-test reproduced conditions in the Duncan Basin as in November, 1943. As changes in the transverse oscillations of the Duncan Basin were not in question, the frequency-band of the test was confined, as before, to periods that would envelop the longitudinal oscillations of the basin. The periodograms for this experiment have already been discussed on p. 297, but in respect of the E/F berth location in particular we note from Fig. 127 that the strong band of critical periods between 6 and 7 minutes, so prominent in Fig. 126, has been reduced to comparative insignificance, leaving only two minor peaks at 5.55 and 6 minutes which might be expected to coalesce to give a beat oscillation of about 5.8 minutes period. In contradistinction, the former 4.3-minute critical period has strengthened into a strong band from 4.3 to 5 minutes.

These results confirm generally the observations for the 1943 period, given in Table II (p. 135). The complete submergence of any oscillations above 5 minutes in the Lea-gauge marigrams for that period and for the following year of 1944 has been explained in Section 100 (p. 298) on the basis of the mild Range-conditions prevailing for that year and the upsetting of the normal regime by the shoal-bank outside the Eastern Mole. The position, it must be realised too, was never static, for dredging operations were proceeding continuously, and their effects were, as steadily, impressed upon the behaviour of the water-mass within the basin.

All these results, taken in conjunction with those of Sections 123 and 124, were considered to have proved the model sufficiently to justify its use in examining means of quelling Range-disturbances in the harbour. The main and final phase of the model experiments was therefore embarked upon.

126. Experimental Procedure in the Testing of Trial-Solutions.

In all the model experiments a certain procedure was followed consistently, which it may be as well to clarify here.

Preliminary cleaning and calibration of the Kymatograph was always undertaken before any lengthy series of tests, but it was not considered necessary to do this daily during continuous testing. Disconnection and emptying of the air-cylinders, before re-connection and immersion, was the only daily operation found to be desirable.

The model was drained sufficiently to expose the sand-bed in the region under the travelling platform, and this area was remoulded and trued to the profiles of the ceiling-suspended templates. The sand-shoreline from Paarden Eiland to Blaauwberg was also remoulded to templates. The depths of the sand-bed in the Duncan Basin below quay-level were specially checked.

The model was then refilled with water to indicator-level at the sump. A check of the level was always made at the harbour, and a daily check in this regard was necessary, although seepage and evaporation losses were generally insignificant.

As all the experiments were directed towards improving conditions in the Duncan Basin, in virtue of its being a new deep-water dock specially built for handling large ships, measurements were mainly confined to assessing the magnitudes of the oscillations in its four corners. The latter were well suited to reveal the worst effects of the seiches prevalent, since they constituted intersection points of boundary-walls in two directions at right angles. The four air-cylinders of the Kymatograph were accordingly disposed in these positions. So long as conditions in the old harbour (Victoria and Alfred Basins) did not deteriorate, there was no special interest in measuring effects there, preliminary tests having shown that very little could be done for the Victoria Basin owing to the proximity of its entrance to the breakwater bight, which forms the antinode of so many external oscillations (cf. p. 311).

The paddles were oriented and adjusted to the settings appropriate to the swell-direction, which for most of the experiments was taken as west-north-west, as we shall see. The paddle strokes were varied for each periodicity according to Fig. 174, and the north and west-paddle speeds were made to differ by 1% of the desired nominal period.

The maximum range of the oscillations in the beat-effect from dual-paddle operation, regardless of phase-differences, was taken as the measure of the disturbance at each recording point. No corections for distortion of the time-scale or the amplitude-scale were made in the presentation of results for the reason that the records were always made comparative as between the existing harbour lay-out and the particular trial-solution being tested.

Where the trial-solution involved no drastic change to the harbour lay-out and could be readily introduced into the model without serious interference with the bed-conditions, it was made during a continuous running of the paddles at the set frequency. By this device exactly comparable conditions could be tested in the existing harbour and the trial-solution without stopping the paddles.

With complicated trial-solutions whose location and alignment were specially important and prevented rapid substitutions without fear of disturbing basin-shapes and bed-levels, it was considered more expedient and, in the end, more comparative to complete a whole sequence of periodicities for each trial-solution in turn, and then, finally, for the existing harbour. The chance of small errors creeping in here to detract from the absolute comparability of trial-solutions with each other and with the present harbour, had to be taken; it was, in any case, the lesser of two necessary evils.

In the preliminary trials no great attention was paid to the stifling of periodicities above about 4 minutes, since by this time it had become apparent, as we shall discuss in the next chapter, that ships were responsive mainly to surges of higher frequency. Initial probings were made to cover a frequency range from 1 to 4 minutes, which was extended to 8 minutes only in the case of promising-looking solutions.

127. Attempts to Abate the Transverse Oscillations in the Duncan Dock.

We have seen that the worst effects of Range in the Duncan Basin, found in the critical-frequency tests of Figs. 124, were recorded for west and west-north-west swell directions (p. 369). In particular the critical periodicities in transverse oscillation were 1.80 and 1.625 mins. (uncorrected) for waves from the west, and 1.825 and 1.65 mins. for waves from west-north-west. The first serious experiments attempted to destroy these oscillations from within, by creating conditions unfavourable to the internal development of fundamental transverse seiches.

The tests were divided into four groups of trial-solutions shown in Figs. 177 (a), (b) and (c). Group A studied methods of subduing the oscillations by means of internal structures, keeping the entrance of the basin in its present position; group B examined the effect of moving the entrance to different positions along the length of the Eastern Mole; group C explored conditions when internal structures were introduced at the optimum position for the 1.825 min. critical periodicity, and group D when the entrance was at the optimum position for the elimination of the 1.65 min. periodicity.

Before embarking on each group of tests, preliminary trials were made to decide which trial-solutions should be recorded. Clearly it would be impossible and unnecessary to record trials which were manifestly of no account, and the solutions depicted in Figs. 177 are to be regarded therefore as the most promising for the given situation.

The results of the group A experiments are presented in Fig. 178, in which the magnitudes of the measured oscillations are given as a percentage of the maximum recorded for the existing basin. The solution which ranks best in this group is seen to be A7, for which the transverse oscillations in all four corners of the dock are in general less than 25%. The results for the west and west-north-west swell-directions are seen to check each other very satisfactorily: on these grounds it was decided to conduct all further experiments for the west-north-west conditions only, which gave the worse results.

In the group B experiments the entrance of the Duncan Basin was moved in steps of 200 feet along the length of the Eastern Mole from its present position at 1250 feet from the corner of A berth to a distance of 3850 ft. (measured to the centre-line of the entrance). In this case the width of the entrance was preserved at its present 400 ft. The results of this series of experiments are shown in Fig. 179, from which it is evident that there is no optimum position for the basin entrance which will subjugate both critical periodicities. The 1.825 min. oscillation is virtually stifled when the entrance is at 3250 feet from A-berth corner, but the 1.65 min. oscillations are then worse than for the existing dock. The latter oscillations, on the other hand, are at their minimum when the entrance is at 1850 ft. from the A-berth corner, but in those circumstances the 1.825 min. seiches are considerably worse again.

In the C group of trial-solutions, the entrase to the Duncan Basin was located at 3250 ft. from the A-berth corner and attempts were made to subdue the 1.65 minute oscillations. It was found that this could only be achieved with a north pier with, or without, an island pier of 'mulberry', a combination suggested by the Chief Civil Engineer, Mr. von Willich (Fig. 180). Trial-solution A7 was incorporated in this series as C9, by way of comparison, and reference to Fig. 180 shows that A7 or C9 ranks best, although admittedly by only a small margin. Trial-solution, C2, for a north pier without a 'mulberry' appears to be quite satisfactory and reduces the oscillation at all corners to less than 25%.

Finally in the D group of experiments the entrance of the basin was located at 1850 ft. from the A-berth corner and the trial-solutions were designed to quell the 1.825 min. seiche. Here it was found that a north pier was alone efficacious, and an island pier of no value. In this test solution A7 was included as D6, which, as Fig. 180 shows, ranks best also in this series.

Solution A7,(Fig. 177 (a)),introducing to the Duncan

Basin a 950 ft. north pier, central between A and E berths, and a 450 ft. stub pier at right angles to the Eastern Mole at a distance of 3250 ft. from the A-berth corner, thus seemed, at this stage, to be the best inhibitor of the transverse oscillations.

128. Frequency-Band Response of Selected Internal Trial-Solutions

Trial-solution A7 was now put to the more rigorous test of revealing its frequency-band response to all periodicities between 0.85 and 4.0 minutes, at intervals of 0.1 minute in the upper region of this range and 0.05 minute in the lower. The comparative periodograms for the existing basin (yellow) and the basin with the addition of the piers (red) are presented in Fig. 181.

It is apparent that although A7 succeeds in ironing out the worst effects of the 1.65 and 1.825 min. oscillations, it begets instead, especially in the A-berth corner of the dock, a band of critical periods between about 2.1 and 2.6 minutes which at present do not exist. At the E-berth corner, moreover, a critical period of 2.7 minutes attains proportions of consequence, and the existing critical band between 3.6 and 4.0 minutes is increased in magnitude. As no scheme could be accepted, which, while curing one ill was instrumental in producing another, A7 had necessarily to be rejected as an antidote to the problem.

It was necessary then to fall back upon such of the other trial-solutions of the A, B, C and D group experiments as offered the next best promise of being satisfactory. Four such were selected, namely, A2, D4, C2 and C5 (Figs. 177), which were redesignated E2, E3, E4 and E5 respectively of a new E-group of experiments (Fig. 177 (a)). For each periodicity in turn measurements were made on E1, E2, ... E6 in consecutive order, so that the tests both started and ended with the existing basin.

The results of these experiments are given in Figs. 182 (a) to (d).

Quite a cursory glance shows that none of these schemes provides an answer to the problem. One and all merely induce other critical oscillations which are non-existent in the present Duncan Dock, and this is largely the result of providing compartments or smaller quasi-basins within the parent basin, which are able to promote resonant oscillations attuned to their own special dimensions.

At the request of the Chief Civil Engineer, Mr. von Willich, however, still further tests were made of trial-solutions employing piers of different lengths at the northern end of the Duncan Basin, with the basin-entrance in various positions. The group L and M trial-solutions illustrated in Figs. 183 (a) and (b) are typical of the variations tried. The entrance was located in four different positions, at 1250, 1850, 2250 and 3250 ft. from the A-berth corner, and for each such entrance-position four lengths of north pier (situated between A and E berths at 800 ft. from E-berth) were tested, namely, 750, 950, 1150 and 1350 ft.

As none of these trial-solutions was any more successful than the K-group, we shall content ourselves with presenting the periodograms for the L-group only (Figs. 184 (a) to (d)), which are typical of the rest. It is much the same story: hampered in one area, the oscillations break out in another, possessed of new critical frequencies and amplitudes of still dangerous proportions.

129. Trial-Solutions of the Outer-Basin Type.

It is convenient here to take stock of the position. By the time the experiments just described had been completed, other researches on ship-reaction to surging in the harbour-basins had evinced the important fact that sea-oscillations of 1 minute period and less could induce resonant surging of moored ships. Moreover, measurements of sea-movements in the Duncan Basin (cf. Table IV, p. 257) had shown that some of these higher-frequency oscillations were by no means inconsiderable. It was evident, therefore, that it was important not only to stifle the transverse oscillations in the Duncan Dock (periods of 1.5 to 1.9 mins.), but, as far as possible, any seiches of higher frequency.

Since the various trial-solutions thus far considered, all of which maintained the entrance width of the Duncan Basin at 400 ft. failed to prevent the ingress of prominent disturbances of periodicities as low as 1.5 minutes, it was clear that the only way to render the Duncan Dock immune to these and higher frequencies would be to constrict the 400 ft. entrance. From the practical navigation point of view, reduction of the entrance-width could not be entertained, and the only way of obtaining the equivalent damping effect was through the medium of an outer basin. A series of experiments was therefore designed to try out selected forms of outer basins, enveloping the Duncan Dock.

Early experiments on the model, (not here described), in which certain shapes of outer basin were tried out, appeared to establish that the use of the present breakwater as one arm of the containing basin was unsatisfactory. Mr. George Stewart's solution* to the Range problem, in particular, involving an extension of the breakwater and the construction of a new breakwater from the Milnerton shore to meet it, was found to be relatively ineffective, largely, it must be supposed, because of the penetrating power of long waves and the absence of any obstruction between the present breakwater and

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*L.c. (ante p. 125), [80].

the shore to prevent a repetition of the existing regime of seiches.

An outer basin within the lee of the present breakwater was found to be far more effective, and the reason for this must lie in the successive thwarting, it provides, of wave-progression, and in the upsetting of the breakwater-shore oscillating system.

In a F-group of experiments certain principles were followed in arriving at the average form of outer basin, as follows:

1. The outer basin should fall within the lee of the existing breakwater, and should envelop the entrance of the Duncan Dock.
2. The entrance to the Duncan Dock should be transferred to a central position in its length and be not more than 800 ft. wide.
3. The entrance of the outer basin should be approximately aligned between the Duncan Basin entrance and the end of the existing breakwater.
4. The long arm of the outer basin should take root on the Eastern Mole near the Sturrock Graving Dock.
5. The outer basin generally should be streamlined to conform with wave-expansion in the outer roadstead.

The first condition was held to be of particular importance in arresting the penetration of high-frequency waves into the outer basin. It imposed a restriction at once on the distance seaward from the existing harbour of the outer-basin entrance.

The second consideration aimed at defeating the 5½ min. longitudinal seiche in the Duncan Basin, which would not be able to develop in serious form if the entrance were located at its node. To assist navigation it was desirable that such a protected entrance should be wider than 400 ft., but 800 ft. was considered to be a necessary limit for the curtailment of undesirable internal effects.

The third principle ensured a direction of approach or departure for ships which would not be far removed from the prevailing wind direction and would thereby assist navigation.

The fourth stipulation was made with the object of avoiding encroachment on the Paarden Eiland shore and interference with the play of forces there. From what has been said of the erosion along the coast near the harbour, (Section 14, p. 40 and Section 102, p. 300), it would clearly be folly to ignore this aspect. To give some length for the absorption of seiches in the outer basin a point on the Eastern Mole near the Sturrock dock seemed a convenient place of offshoot for the long arm.

The fifth and final consideration sought to permit proper expansion of swells in by-passing the harbour, without removal of any more spending beach than has at present been taken from the bay. It required in essence that the long arm of the outer basin should lie along the natural flow-lines of the waves expanding past the breakwater. If this principle were followed, the outer basin, so far from being harmful, should be beneficial for the reason that it would trap a fair proportion of refracted wave energy curving round the end of the breakwater, while affording a gradual expansion and even distribution of the remainder on the present spending beaches. More particularly, the streamlining would prevent undesirable reflections of incident ground-swells such as at present occur at the Eastern Mole (cf. pp. 251, 270), and would thus assist materially in inhibiting standing-wave formation and, ultimately, erosion.

Application of these five principles practically determined the shape and size of the outer basin within fairly narrow limits and trial-solutions F, H and J (Fig. 183 (a)) are typical of what seemed possible on this basis.

The periodogram test-results for the F-group of trial-solutions are contained in Figs. 185 (a) to (f). On the whole they are very promising and indicate that most of the serious short period oscillations can be virtually eliminated in the Duncan Basin. Solution F2 probably ranks best among the F-group, judged solely on its performance in stifling the transverse oscillations. There is perhaps not much to choose between F1, F2 and F3, but the superiority of all of these over F4, F5 and F6 is so definite as to prove the advantage of having the short arm of the outer basin normal to the A-berth pier.

The longitudinal oscillations in the Duncan Basin, though reduced in magnitude, are not eradicated. In point of fact, however, the low frequency oscillations in the F-group schemes are not really longitudinal for the Duncan Basin at all, but, rather, diagonal as between the outer basin and opposite ends of the Duncan Dock. The persistence of strong periodicities of this order (5½ minutes) is not of very serious consequence as they are of relatively small account in disturbing ships moored at the quays; of which aspect more will be said in the next chapter. In general, therefore, it can be said that the total effect of an outer basin such as F2 is very satisfactory and approaches the ideal of a perfect solution.

Two variations of the F-group trial-solutions were then tested in the form of H and J (Fig. 183 (a)). The second opening was introduced in H with the idea of quelling the diagonal oscillations referred to above, but this scheme, on being tested first for efficacy over the high-frequency band, was found to fall so far below the standards of the F solutions that it was abandoned.

The periodograms for trial-solution J (Fig. 186) give perhaps the best performance of any in flattening out the oscillations in the high frequency band, and the reason for this may clearly be ascribed to the successive choking provided by the double outer basin. Solution J, on the other hand, gives more critical diagonal oscillations at $5\frac{1}{2}$-$6\frac{1}{2}$ minutes than the F-group. It lost favour finally through its propensity for developing treacherous currents through the chain of entrances at the longer periodicities (10 to 20 mins.), as these would undoubtedly constitute a hazard to the safe passage of ships.

Modifications of the J trial-solution were next tried with a view to avoiding proximate entrances; the N-group of Fig. 183 (b) represent the variants. In N1 the entrances have merely been placed farther apart, while in N2 and N3 the opposite arms of the outer basin are staggered so as to compel penetrating waves to have a sinuous curving action round the ends of alternate arms.

The periodograms for the N-group experiments are shown in Figs. 187 (a), (b) and (c), from which it is readily seen that N1 and N2 are considerably better than N3 in the higher-frequency range of oscillations. Solution N1 is somewhat more efficient than N2, but the latter nevertheless fulfils the requirements of a complete solution in that it reduces all oscillations of periods less than 4 minutes to less than 25% of the oscillation at the E-berth corner of the existing Duncan Dock. For being minus the pier abutting on the Elbow, scheme N2 is obviously preferable to N1.

The derivation of this criterion is given in the next chapter.

130. A Solution to Range-Action in the Duncan Basin.

The F2 and N2 lay-outs could now be said to have evolved as real solutions of the Range problem in the Duncan Basin. To draw the final comparison, the F2 solution was now retested under the same conditions as prevailed for the N2 trial, for the reader will no doubt have remarked on the considerable differences in the existing-harbour (yellow) periodograms of Figs. 185 and 187 (cf. p. 385).

The results of re-testing F2 (P series) are shown in Figs. 188 (a) and (b), of which (b) now includes measurements made at four points in the Victoria Basin. Fig. 188 (c) gives the comparable effects of the N2 solution on the Victoria Basin.

Comparing the N2 and F2 schemes for the Duncan Basin (Figs. 187 (b) and 188 (a)), we see that F2 is slightly more efficient in quelling the high-frequency oscillations, but is somewhat less efficient for periodicities above 4 mins. The comparison of effects in the Victoria Basin, however, (Figs. 188 (b) and (c)), shows that F2 is outstandingly better than N2. The latter, in fact, seriously increases the magnitude of the Range effect in the Victoria Dock, while the former diminishes it. A particularly bad feature of the repercussions of N2 upon this basin is the enlargement of the oscillation at about 1.35 minutes. These further tests therefore rule out scheme N2 as a tenable solution, and F2 emerges as the only really satisfactory one from all points of view.

Up to this stage all the outer-basin trial-solutions had been tested with depths in the basins as they existed in 1946. As adoption of any scheme such as the F2 solution would require dredging at the south end of the Duncan Basin, further tests (Q series) were undertaken to examine this aspect. The results (Figs. 189 (a) and (b)) show that by dredging to -40 ft. (LWOST) over the whole of the Duncan Basin, the residual oscillations which penetrate into this dock are somewhat increased, but not sufficiently to invalidate the F2 scheme as a solution. In the Victoria Basin the P series test-results are confirmed, conditions being relatively unchanged. The P and Q series tests indicate that if the F2 solution were ever adopted, it would be desirable to restrict dredging of the south end of the Duncan Basin to a minimum consonant with the safe navigation of ships. Fig. 190 is a photograph of the F2 scheme as it looked during trial in the model, and Fig. 191 is a detailed plan of its lay-out showing the streamlining in relation to incoming waves.

This concluded the programme of model-testing up to the end of the author's stay at Cape Town (December, 1946). At this time of writing (1951), further tests are again in progress to decide along what lines the future expansion of Table Bay harbour should take place. The ultimate recommendation for a practicable scheme will be the responsibility of a Special Committee of the Railways and Harbours Administration. As this is matter of policy, it is not the author's intention to go further into this question in these pages, suffice it to say that the principle of the protected outer-basin seems to have been accepted as the desirable mode of development.

CHAPTER XVI

THE EFFECT OF RANGE ON SHIPPING.

> ".... the methods of the mathematician can give us a full and final answer, while those of the experimentalist only give a partial answer".
>
> —— Sir James Jeans,
> Sir Halley Stewart Lecture,
> 'Man and the Universe', (1935).

131. Damage Caused by Range-Action.

In Section 6 (p. 22 et seq.) we described some of the troubles that have been experienced in Table Bay Harbour as a result of Range-action. In the light of what has been gleaned about the phenomenon in preceding pages, it is now clear that the unpleasant motion of ships caught in its spell arises from bulk movements of water responding to the seiches within the harbour basins. It is not difficult to see that at the antinodes of the seiches, where the water movement is mainly vertical and horizontal displacements are small, ships are not seriously endangered. It is the nodal areas, where horizontal movement is strong, that are more particularly dangerous, for the periodic accelerations imparted to ships in these places constitute the inertia forces that must be resisted by the moorings, fenders and harbour structures.

Where the nodal areas of the seiches occur at the mouth of a basin, the periodic currents affect only the navigation of ships, and damage can occur only when ships are swept out of control and brought into contact with fixed structures or other vessels. This has happened several times in the 'cut' between the Alfred and Victoria Basins (pp. 23, 27), and several narrow escapes have been experienced at the mouth of the Duncan Basin, (Section 50, p. 146). We know now that severe currents can occur in the entrances of the Alfred and Victoria Basins with fairly large amplitude seiches of periodicities of 4½ mins. upward, and that the strong seiches of the bay, of periods from 17 to 22 minutes, induce the dangerous surges through the opening to the Duncan Basin (cf. pp. 151, 300).

Where the nodal areas of seiches inside the basins abut on the boundary-walls, ships are liable to be disturbed, and damage is possible if circumstances are propitious for climactic movements. If the ship movement is mainly longitudinal in the seiche current and parallel to the quay, the worst that can happen is that the ship will ultimately break her moorings and collide with some adjacent ship or with a corner of the dock: but if the movement is lateral, as when the node of the seiche makes oblique intersection with the dock-boundaries, the ship may collide with the floating fenders and the quay with impact sufficient to buckle her shell-plating and bulkheads and crush the fenders to fibres. Such cases are, of course, extreme.

Fortunately, the occasions on which severe damage is sustained at Cape Town are comparatively rare. The worst troubles were experienced during the years 1940 to 1942 which were exceptional as regards the frequency and magnitude of Range-action: the winter of 1941, in particular, from the rainfall point of view, was one of the worst since 1900. Cyclic weather changes, presumably, leading to a diminution of Range intensity in combination with a sharp decline in shipping density after the war and other factors (cf. p. 51), have since reduced the hazard. Ordinarily, the only damage occurring is a certain amount of rope-wastage from abrasion and fracture, which from long experience has come to be regarded by the port authorities as a normal maintenance expense.

The actual number of occasions per year over the period of 1940-45 that ship's ropes have fractured as a result of Range-action is portrayed in Fig. 191*. One notices from this diagram that there is no hard and fast relationship between the magnitude of Range-action and the number of rope breakages. Thus the severe Range-occurrence of June 12/13th, 1940, caused only 4 or 5 rope breakages in the Duncan Basin, whereas the less severe Range-action of September 23rd, 1941, caused 25 failures in that dock alone. A difference in the number of ships in port on these two occasions could explain this anomaly no doubt, but it is probable that other factors are also involved.

We may summarise the contents of Fig. 191 in tabular form for convenience of comparison, as follows:

Table XVII: Rope Breakages in Relation to Range-Action.

Year	No. of Occasions of Rope Breakages			Average Amplitude of Range-Action (ins.)		Average No. of Ropes Broken per Occasion	
	Duncan Basin	Victoria Basin	Both Basins Simultaneously	Duncan Basin (Period 1.8mins)	Alfred Basin (Period 5.5mins)	Duncan Basin	Victoria Basin
1940	22	24	31	4.1	8.4	4.2	2.6
1941	31	24	39	2.9	7.3	2.8	2.2
1942	30	20	37	2.2	5.9	3.6	1.7
1943	23	10	27	2.3	6.9	1.8	0.7
1944	14	8	16	2.3	6.1	2.1	0.8
1945	14	3	15	2.5	6.4	2.7	0.9

The fact that so many rope failures occurred in 1942 when the magnitude of Range-action on the average was less than in other years must be attributed to the larger number of ships concentrated at Cape Town during that year of the

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* This does not include the considerable number of ropes condemned and discarded because of frayed condition.

war. The last two columns of the above table, giving the average number of ropes broken per occasion of Range-action are valid in only a very general way, because some individual occasions gave rise to a large number of breakages. Nevertheless, the lessening of effects in the later years is well borne out by the figures. It will be seen that even in the worst years of Range-action there were only about 40 occasions (at a round figure) per year on which the Range was severe enough to cause the parting of ropes.

132. Measured Frequencies of Oscillation of Ships during Range.

Apart from the position of a moored ship in relation to the nodal areas of seiches within the harbour and the strength of the surges, there are likely to be other factors governing the behaviour of a ship during Range-action, such as its mass and draught, the number of ropes holding it, their degree of tightness and resilience, etc. But the important question insofar as the harbour at Cape Town is concerned, is to know just what periodicities of seiches are critical for the sizes of ships likely to patronise the port, and within what maximum limit the amplitudes of such seiches would have to be controlled to render the Range disturbances innocuous.

The problem, as we have seen (Section 28, p. 80), was approached in the first instance by measuring ship movements in relation to the rise and fall of the sea in the immediate vicinity of the ship being observed. Figs. 22 and 23, already given, reflect early efforts in this direction, while Figs. 193 to 196 present the results of later measurements.

For an adequate interpretation of these sea and ship oscillations it was necessary to isolate the harmonic components giving rise to them. The various curves were therefore subjected to Residuation analysis (cf. Section 89, p. 255), some of the results of which are portrayed in Fig. 197: this figure applies specifically to the oscillations recorded in Fig. 194. The salient features of the diagrams of Fig. 197 and of the analyses of the remaining data of Figs. 22, 23, 193, 195 and 196 are set out in Table XVIII below:

Table XVIII: Correlation between Ship Movements and Sea Oscillations.

Name of Ship & Date	Displace-ment Tonnage (Tons of 2240 lbs)	Dimensions (ft)			Berth occupied (cf. Fig. 4)	Component Oscillation in order of Maxm. Amplitudes (periods in mins.)					
		Length between perpendiculars	Beam	Draught when observed		Sea Osciln. nearby		Ship Osciln.			
								Longitl.		Lateral	
						1	2	1	2	1	2
HMS. 'Le Tigre' 20/6/45	2000	220	35	-	Cross Berth	1.90	0.88	0.55	0.80	-	-
'Dahlia' 7/7/45	6400	421	55	13	C	1.76	0.55	0.30	0.50	0.30	0.50
'William Bradford' 30/8/44	7500	423	57	15	C	5.55	1.00	0.96	1.86	-	-
Blockship 19/7/44	9000	350	50	22	Eastn Mole	4.20	1.60	0.38		-	-
'Erica' 6/8/46	10500	405	53	17	A	1.57	5.35	0.55	0.75	0.43	0.70
'City of Swansea' 22/7/46	10900	400	52	28	E			0.90	1.50	0.80	2.10
'Anna Howard Shaw' 31/7/45	13400	423	57	27	D	1.86	0.72	0.50	0.70	0.55	0.70
'Defoe' 7/12/45	14000	439	62	26	A	5.60	1.75	1.00	0.58	-	-
'Charles Paddock' 18/8/45	14300	422	57	29	F	1.50	5.50	0.45	1.00	2.72	0.85
'Umtata' 6/8/46	15300	453	59	21	C	4.00	5.87	1.53	0.53	1.35	2.65
'Oranjefontein' 23/8/46	17900	499	63	27	C	17.0	0.80	0.55	1.55	1.30	2.12
'Carnarvon Castle' 23/8/46	25300	661	74	28	A	1.44	1.00	0.72	1.55	2.00	1.10
'Dominion Monarch' 12/7/43	35000	658	85	30	B	1.50		1.65		-	-
'Pasteur' 3/8/44	37000	671	88	30	A	1.00	0.50	0.78	2.40	-	-
USS 'California' 17/11/45	42000	624	98	31	K	5.58	1.50	1.79	5.87	-	-
'Nieuw Amsterdam' 21/6/45	47700	759	88	33	A	0.68	0.50	1.02	1.40	-	-

In Table XVIII we may recognise in the columns giving the principal sea oscillations, some of the periodicities that were specified in (37), (p. 288). Although these components were the most prominent in the recorded vertical sea-movements, it should be remembered that there may have been other components that were nodal at the seichometer positions, which could have been potent factors in influencing the ships, while going unrecorded.

One of the remarkable things about this tabulation is that despite the enormous variation in the displacement tonnages of the ships observed, there is no very considerable equivalent variation in their periodicities of oscillation. One fact emerges positively, that it is the relatively high frequency disturbances in the harbour (periodicities below about 2 minutes) that have the greatest effect upon shipping. In particular, periodicities of the order of 1 minute and less, down to say 20 seconds, appear to be most critical and seem to be able to influence the largest and the smallest vessels alike We may note, however, a tendency for the larger ships to vaccillate at somewhat longer periods than the smaller. There are, nevertheless, certain inconsistencies. During the course of the researches at Cape Town, these seemed considerable enough to warrant an excursion into the theoretical realm for their elucidation. At that time many of the results given in Table XVIII were not yet available and the behaviour of ships was often completely baffling, severe conditions of Range sometimes producing no ill effects, and mild conditions at other times causing considerable trouble.

133. The Theoretical Problem of Ship-Ranging.

An examination of the movements of model ships in the harbour model (Fig. 148 (b)) showed an important difference between the motion of hulks free to displace in the periodic current of a seiche and those restrained by mooring ropes. A free ship performed exactly the motions of the water-particles, almost as if it were an integral part of the water-mass: a moored ship, on the other hand, provided that its permissible travel was less than the overall horizontal displacement caused by the seiche, was pulled back by its ropes so as to oscillate out of phase with the seiche current. This fact stressed the importance of the ship's moorings and led the author to approach the problem as one of damped vibrations of a spring-suspended mass. The springs in this case were the ship's ropes, which, unlike the simple mechanical springs of most vibration problems, are governed by a complicated exponential tension-displacement law.

This phase of the research has been fully described in a paper recently published by the American Society of Civil Engineers* and will not be repeated here except insofar as it is necessary to quote results for the expansion of our theme.

It was shown that the critical periodicity of longitudinal ship-oscillation is determinable from the relationship

$$\tau = \frac{2\pi}{A}\left(\frac{d}{g}\right)^{\frac{1}{2}}\left(\frac{4WA^2}{Nkd}\right)^{\frac{1}{1+n}} \qquad \text{———————— (62).}$$

in which A is the amplitude of the seiche, d the depth of water in the harbour basin, W the displacement tonnage of the ship, N the total number of mooring ropes holding the ship, k a constant and n a numerical exponent in a relationship governing the longitudinal horizontal component of tension T_x induced in an individual rope as a result of a displacement u of the ship from equilibrium position. This relationship in particular takes the form:

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* Wilson. 'Ship Response to Range Action in Harbor Basins', Proc. ASCE, Vol. 76, Nov., 1950, [123].

$$T_x = ku^n. \qquad (63)$$

Equation (62) is strictly applicable to a ship lying at the node of a seiche, the movement of which is parallel to the ship. The basin is considered to be vertical-walled and of uniform depth.

The critical periodicities for various seiche-amplitudes according to this equation were evaluated for a ship of average size ($W =$ 14200 tons) such as uses the port of Cape Town, and Fig. 198 reproduces these for three conditions of the moorings, namely, when the ropes are initially nearly taut, when they are tighter than average, and when they hang with an amount of sag which from measurement was found to be about the average condition of moorings at Cape Town. These conditions have been catered for in the values of k and n shown on the curves A,B,C and D (Fig. 198). The corresponding rope-tensions for the three cases are given by the curves E, F and G.

Now, tension tests that were made of new and old steel and coir ropes, such as are normally used for mooring purposes at Cape Town, showed that under the effects of fatigue and age, the ultimate strength of the coir ropes was not above from 10 to 20 short tons (Fig. 199). These rope-tensions, it will be seen from Fig. 198, are met when seiche amplitudes are above about 0.7 ft., and periodicities below about 40 seconds. It would thus seem to be the high-frequency seiches of large magnitude that are really critical for ships.

A ship will tend to resonate with a seiche of longer period than 40 seconds when the amplitudes of the disturbance are small. Thus a seiche of 1 minute periodicity will produce resonant motion in the average ship with average moorings (curves A or B) when the seiche amplitude is about 0.35 ft., but under such conditions curve E shows that the tensions developed will not be above 2 tons and therefore quite insignificant. The general inference is that long-period seiches, such as the $5\frac{1}{2}$ min. longitudinal, and even the 1.5-1.9 min. transverse, are not of serious consequence for the average ship, except insofar as their effects may be additive to the critical motion of some higher frequency.

By making the ropes as tight as possible we see from Fig. 198 that we court the risk of reducing the seiche-amplitude at which critical tensions (say 10 tons) can develop, but, as against this, we also lower the periodicity of the seiche that can produce resonance. In such circumstances it is only 20 second waves of large amplitude that can cause any damage and these are usually the ones that a harbour is best able to quell.

The size of the ship does not appear to affect the issue very greatly, for its influence is felt only through the $(n+1)$th root of the displacement tonnage, W , in equation (62). This statement is true, however, only so long as the change in W does not involve any serious change in the catenary-suspension of the mooring ropes. If the change in W involves a large variation in deck-height then the critical periodicities are more aptly given by the following relation:

$$\tau = \pi r \left(\frac{d}{g}\right)^{\frac{1}{2}} \frac{H^2}{A L_0} \qquad \text{———————— (64)}$$

in which the new symbols H , L_0 and r are respectively the height of the ship's fairlead or rope-guide above the quay bollard, the horizontal distance of the fairlead from the bollard for rest position of the ship, and the ratio by which the maximum travel of the ship under resonance exceeds the travel that would just tighten the ropes. The value of r can be shown to lie between 1 and 2.

Fig. 200, which is also reproduced from the author's paper, evaluates the critical periodicities on the basis of equation (64) for three ships, one the average ship we have already considered, another of size (W= 50,000 tons) comparable to the 'Nieuw Amsterdam (Table XVIII), and the third a low-lying vessel such as a tanker. Curve A for the average ship (Fig. 200) is found to agree very largely (as it should do) with curves A or B of Fig. 198. Curves B and C apply to the large and small ships respectively, while D, E and F give, as before, corresponding rope tensions for individual ropes. The assumption underlying Fig. 200 is that the ropes in all three cases hang so that the tangents to their catenaries at the quay-bollards, for rest-position, are horizontal.

We now find that very large ships will only resonate dangerously in very large amplitude seiches, for the 50,000 ton ship requires a seiche of about 65 seconds periodicity and $1\frac{1}{4}$ ft. amplitude to induce rope-tensions bordering on 10 tons. The ships likely to be most dangerous are sizes intermediate between 9000 and 14000 tons with deck-heights between 5 and 18 ft. above quay level, for then the areas between curves A and C and between D and F (Fig. 200) pertain, and rope-tensions of 10 tons and more can be registered with seiches of periods between 10 and 50 seconds and amplitudes from 0.35 to 1 ft.

The conclusion we draw from all this is that the periodicities that are most critical for ships in longitudinal ranging are less than about 70 seconds. A similar conclusion can be reached theoretically in respect of transverse ship motion*. Both deductions are generally supported by the results of Table XVIII. If, then, a harbour can be made reasonably immune to

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* L.c. (ante p. 392), [123], pp. 18-21; see also p.415 (post).

serious commotion from these high frequencies, Range-action should largely be rendered impotent.

134. Experimental Confirmation of Theory.

To check the principles evolved in this theoretical study a glass-sided tank and mooring carriage were designed for experiments on model ships, (Figs. 201 and 202). The tank was 6 ft. long and carried two adjustable partitions, one of which had a port or opening in the bottom. The latter was used for partitioning off one end of the tank as a displacer-well within which a plunger was caused to rise and fall with simple harmonic motion (Fig. 201). The second partition was used for varying the effective length of the tank. The whole assembly was somewhat similar to the apparatus devised by E. Maclagen-Wedderburn to demonstrate the nature of seiche-action[*]

The mooring carriage was constructed of Meccano parts and was designed to rest on the tops of the glass sides of the tank (Fig. 202). The suspension-points for holding the moorings of a model ship were below the main body of the carriage frame, a central handwheel controlling their closing or opening through rack-gearing. Each sliding saddle carried a hand-wheel which permitted raising or lowering of the suspension-points. By rapid and simple adjustments it was thus possible to elevate or depress and open or close the 'fixed bollards' so as to increase or relieve tension in the model ropes, as desired.

By actuating the displacer and causing a periodic flux through the well-partition, the water in the trough could be set in oscillation. A uninodal seiche could then be arranged for any periodicity by appropriately placing the movable partition. The performance of a ship at the node of a seiche under

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[*] Cf. Chrystal, (l.c. ante p. 84), [41], pp. 647-649.

the restraint of its mooring ropes could thus be observed critically through the walls of the tank.

Model ropes used in the tests were prepared from rubber bands of various thicknesses, the end loops of which were cemented round rubber 'thimbles' or thin slices of rubber tubing (Fig. 202). The properties of these rubber 'strops' were determined by simple load-extension tests and are presented graphically in Fig. 203. Provided that the loads and deflections were kept reasonably small the rubber strops could be collected into three groups (A, B), (C, D), (E, F, G, H, K, L) defining different grades of resiliency.

Before undertaking any model experiments calculations were made on the basis of equation (62) to determine the critical periods of oscillation for various sizes of model ships. The latter were made of wood to the same scales as the harbour model, and were weighted with lead to give them correct buoyancy. Their distortion was of no consequence, because there was no question of interpreting the model results on a prototype scale, but only of checking principles as applying to the model conditions.

It was necessary first of all to assess the values of k and n in equation (63), (p. 393) applicable to the model ropes. Here it should be noted that the curves of Fig. 203 do not express any relationship between tension T_x and ship displacement u, but only between tension T and rope extension ∂s. The evaluation of ship displacement from rest position proceeded as follows:

Let s be the initial length of the rope (unstrained), assumed to be hanging in a catenary: let l be its horizontal and h its vertical projection. The amount by which the ship can displace horizontally so as to draw the catenary into a straight line (without rope extension) is thus

$$\partial l = \sqrt{(s^2-h^2)} - l \quad \text{\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_}(65)$$

If the additional horizontal displacement of the ship in virtue of the extension ∂s of the ropes be ∂u, then it may be shown that

$$\partial u = \left(\frac{s}{l+\partial l}\right).\partial s \quad \text{approximately \_\_\_\_\_\_\_\_\_\_\_\_}(66).$$

The total ship displacement longitudinally from equilibrium position is thus

$$u = \partial l + \partial u \quad \text{\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_}(67).$$

Use of equations (65), (66) and (67), together with the data of Fig. 203, enabled the plotting of relationships between Log T and Log u for specific values of $s = 11.0$ and 6.0 cms and $h = 3.5$ cms, and for different values of l. In terms of equation (63), these curves should all be straight lines, but owing to the difficulties of simulating the prototype rope conditions on a model scale, the author had to be content with the deviations from the straight shown in Fig. 204. Values of k and n were estimated from the maximum slopes of the curves, which made them strictly applicable for only small rope-tensions and ship-displacements.

The values of n when plotted against the horizontal projection of the rope l, were found to conform to the linear relationships shown in Figs. 205 (a) and (b). The values of k were related to by the curves of Fig. 206.

The calculations of critical periods according to equation (62) were then made for $d = 9$ cms, $A = 0.7$ cm, and $N = 2$ for various ships equivalent in size to the 'Queen Mary', 'Winchester Castle', cargo vessel and tanker. The results for the longer length of ropes used ($s = 11$ cms) are shown in Figs. 207 (a), (b) and (c) plotted against values of the horizontal projection of the rope l. In passing we may note from these graphs that the size of ship has no great influence on the critical periods of oscillation, confirming our remark on p. 394; nor, as it turns out, have the differing resiliencies of the three groups of model ropes.

In seeking experimental confirmation of these predictions the procedure followed was to take different lengths of oscillating basin and adjust the speed and amplitude of the plunger so that a uninodal seiche of amplitude $A = 0.7$ cm in a depth of water of 9 cms was created. The mooring carriage, holding a ship with an appropriate pair of ropes, was then placed over the node of the seiche as in Figs. 201 and 202, and the handwheels were adjusted to give the correct vertical projection of the ropes $h = 3.5$ cms, with the ropes initially taut. Under this condition it was found that the ship would ride out any periodic current of a seiche without developing resonant motion, showing that perfectly tight ropes, if they were feasible in practice, would be a cure for longitudinal ranging.

By operating the central handwheel of the mooring carriage, the suspension points were then moved towards each other so as to slack off the ropes and permit the ship to oscillate with the nodal surges. The carriage itself, of course, was locked to prevent movement on the glass sides of the tank. By slow adjustment a stage would be reached at which the ship would oscillate most violently for the given frequency and beyond which the motion would become unstable and lose all resonance. The dimension between centres of sliding saddles could then be measured and the value of the horizontal rope-projection l, corresponding to the periodicity, determined.

The experiments supported the theoretical calculations generally without giving precise checks. The lack of preciseness undoubtedly lay in the fact that too large an amplitude of seiche was adopted for the calculations, (which were done beforehand), thereby calling into play rope-tensions of such magnitude as to invalidate the use of the values of n and k adopted in the theory. It was found later that rubber strop extensions reached 1 cm or more as against a maximum value of 0.2 cm permissible for the values of n and k used. A few of the calculations were reworked for a smaller seiche amplitude of 0.3 cm, in lieu of 0.7 cm, when excellent correspondence was obtained in repeat-experiments.

135. The Mechanism of Longitudinal Ship-Oscillation.

These experiments served to uncover an important fact, that resonance in ship oscillation is attained when the amount of play ∂l, (equation (65)) is of the same order as the amplitude of the seiche-movement ξ_{max}. Actually it was found that the model ship would resonate when ξ_{max} exceeded ∂l by a factor r (p. 394) with a value between 1 and 2.

The value of ξ_{max} at the node of a seiche may be found by integrating equation (38) with respect to time or, alternatively, from equation (14)-(i) with the appropriate approximations: thus

$$\xi_{max} = \frac{A}{q.d} \qquad \text{(68).}$$

From observation, therefore,

$$\xi_{max} = r.\,\partial l \qquad \text{(69).}$$

By the use of equations (3), (5), and (8), (p. 107), and (65), equations (68) and (69) lead to the result that

$$\tau = \frac{2\pi r}{A}\left(\frac{d}{g}\right)^{\frac{1}{2}}\left(\sqrt{s^2-h^2}-l\right) \qquad \text{(70).}$$

Equation (70) expresses a relationship between τ and l and may therefore be compared directly with the curves of Figs. 207. The latter all approximate to straight lines whose equations take the form

$$\tau = G(\sqrt{s^2-h^2} - l) \qquad (71)$$

the gradient G of which has the measured values 0.839, 0.804, and 0.818, corresponding respectively to Figs. 207 (a), (b) and (c). The mean gradient from these figures is 0.820.

Now, equation (70), which may be considered to be an experimental deduction, is also of the form of (71) and yields a gradient value $G = 0.824$ for $A = 0.7$, $d = 9.0$ and $g = 981$ cms, taking $r = 1$. The agreement here is very satisfactory and establishes the identity of equations (62) and (64)[*], since (64) is merely an adaptation of (70).

We may see now, too, why the original experiments with the model ships gave rather poor correspondence with Figs. 207. The experimental conditions, in causing violent surging, inevitably made the ropes extend elastically by fair amounts, thereby making r greater than 1, whereas the assumptions of the calculations, in requiring small rope tensions and extensions, gave r, in effect, a value approaching unity.

The model experiments can be said to have confirmed the theory in showing that resonance conditions in the motion of a ship ranging longitudinally will prevail when the seiche has the periodicity and amplitude and the ships ropes the slackness governed by the relationship of equation (70) or (64). Equation (62) is also confirmed as the same condition expressed in another form.

136. Theoretical Concepts Governing Rope Breakages.

With the pleasing agreement thus established between theory and experiment, it was possible to use the theoretical weapon in other directions. The question at issue was to know

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[*] This identity was proved in another way in the author's paper (l.c. ante p. 392), [123], p. 14.

what reduction in magnitude of the Range-disturbance is necessary to ensure safety for shipping, assuming that the maximum effects that can occur are of the same order of magnitude as those experienced in the years from 1940 to 1942. To answer this point it becomes necessary to know what damage a particular magnitude of Range-action is capable of causing.

We may approach this problem by estimating the forces imposed on the mooring gear of a ship when the latter attains maximum acceleration at the end of the surge caused by a seiche. This maximum acceleration will be given by equation (39), (p. 301), when $\sin(pt+e) = 1$. Since the longitudinal component of pull which this acceleration would impose on the mooring ropes comprises both the inertia force of the ship, $(W/g)\ddot{u}_{max}$, and the pressure of the water, $(W/g)\ddot{\xi}_{max}$ [*], and since the maximum accelerations of ship and water mass will be the same, we may write the collective rope tensions as

$$\Sigma T_x = \frac{2WAp^2}{g.q.d} \sin qx.$$

By the use once more of equations (3), (5) and (8), (p. 107), and of (18A), (p. 237), this result can be transformed to

$$\Sigma T_x = \frac{4\pi A W}{\tau\sqrt{gd}} . \sin \frac{m\pi x}{L} \qquad \text{(72)}$$

where L is here the length of the side of the basin along which the ship is moored, x the distance to the centre of the ship from one end of the quay, and m the nodality of the seiche of periodicity τ. At the node of a uninodal oscillation, for which $m = 1$ and $x = L/2$, the value of the sine is unity. The same is true at the node of any of the higher harmonic oscillations for which $m = 2, 3, \ldots.$ If we replace the sine by a factor α and note that the mean water depth, d, is not greatly affected by the variation of tide-height at

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[*] L.c. (ante p. 392), [123], p. 10.

Cape Town, we may express (72) more simply as

$$\Sigma T \propto \frac{AW\alpha}{\tau} \qquad \text{———————(73).}$$

The suffix to T has here been discarded, for the horizontal component of rope tension parallel to the quay, T_x , is roughly proportional to the full rope tension, T, at the angle of obliquity which mooring ropes usually make with the line of the quay.

Now steel or coir ropes under tension are subject to fatigue from alternating stress in much the same way as structural members in machines, and we could expect some falling off of ultimate strength with time or number of reversals of stress. This is clearly proved in Fig. 199, for the old ropes in repeated loading tests returned very much lower ultimate strengths than the equivalent new ropes. Denoting the ultimate strength then by U , we could expect U to be inversely proportional to the time, t , that a rope is in service, so that

$$U \propto \frac{1}{t} \qquad \text{———————(74)}$$

If, during severe Range-action, the rope tensions called into play rise above the safe limit into the region of the ultimate strengths, with a specific value U_1 , the time that the ropes can withstand the strain according to (74) will be t_1 , after which they will break. Assuming that the duration of the incidence of Range-action, t_2 , is greater than the life of the rope at this tension, a rope will be broken at every interval of time t_1 , and the number of replacements of a particular rope in the time t_2 will be t_2/t_1 . For N ropes holding the ship, there will then have to be $N(t_2/t_1)$ replacements during the spell of Range, or the number of ropes broken, ν , will be

$$\nu = \frac{Nt_2}{t_1} \propto N t_2 U_1 \qquad \text{———————(75)}$$

In equation (73) the total pull ΣT on the ropes at one end of the ship will be $U_1 N/2$, in terms of our assumption, so that

$$U_1 N \propto \frac{A.W\alpha}{\tau},$$

whence by the use of (75) in eliminating the product U_1N,

$$\frac{\nu}{t_2 N} \propto \frac{AW\alpha}{\tau N}. \qquad (76)$$

The right-hand side of expression (76) is thus representative of the number of ropes broken per unit of time per ship. In port records at Cape Town the number of rope breakages per ship is usually recorded per 24 hours, and if this number be denoted by n, this symbol may be used to replace $\nu/t_2 N$. so that (76) may be rewritten:

$$n \propto \frac{AW\alpha}{\tau N}. \qquad 77.$$

In the event of a ship breaking one or more ropes, the remainder are, of course, subjected at once to larger tensions which tend to increase the rate of fracture of the rest. It is impossible in a generalisation of this problem such as this, however, to cater for such conditions, for the supposition is that berthing staff immediately undertake the replacement of the ropes to ensure the safety of the ship.

If as a criterion of the magnitude of the Range action we take the amplitude of a prominent periodicity which is always present, such as the transverse oscillation in the Duncan Dock or the 5½ minute surge in the Alfred Basin, we may consider the period, τ, in (77) to be constant. A statistical examination of the amplitudes, A, of these prominent seiches in relation to the number of ropes fractured, could then be expected to reveal, on the basis of (77), that

$$\frac{1}{A} \propto \frac{W}{N}\cdot\frac{\alpha}{n} \qquad (78)$$

Now the relationship between the displacement tonnage of a ship, W , and the number of ropes, N , normally used in mooring her, has been found to take the linear form shown in Fig. 208. Berthing staff apparently apportion mooring ropes according to their judgement of the situation and do not work to any specific rules, and this accounts for the rather considerable variations reflected in Fig. 208. Nevertheless, as might be expected, the number of mooring ropes appears to be roughly in proportion to the size of the ship, and (W/N) in (78) is therefore approximately constant.

Since the ratio (n/α) is representative of the number of ropes broken at a particular location or berth, it follows from the approximate constancy of (N/W), that the product $(Nn/W\alpha)$ also reflects the number of ropes broken at a particular berth. Accordingly, if m berths in a single harbour basin are occupied by ships during an occurrence of Range-action, the total number of ropes broken will be given by $\sum_1^m (Nn/W\alpha)$, which from (78) should make

$$\sum_1^m \left(\frac{N.n}{W.\alpha}\right) \propto mA.$$

From this, by writing

$$\frac{1}{\beta} = \frac{1}{m} \sum_1^m \left(\frac{N.n}{W.\alpha}\right), \qquad (79)$$

we may expect to find a hyperbolic relationship between β and A , such that

$$\frac{1}{\beta} \propto A \qquad (80).$$

137. Relative Susceptibilities of Berths to Rope-Breakages.

In Chapter III, (pp. 49, 54, 61) we recorded nautical opinion on what it considered to be the best and worst berths in the Victoria and Duncan Basins. For the practical implementation of our present theme, it was necessary that some quantitative measure of these differences in susceptibilities of berths to effects from Range-action should somehow be obtained.

This phase of the problem was approached by assessing the number of occasions that ships parted ropes at a particular berth, as a fraction of the number of occasions that the berth was occupied over the period 1940-46. Details of this study are given in Table XIX, (p. 407).

As an example of the interpretation to be placed on the data contained in Table XIX, consider any particular berth in the harbour, say the outside of No. 2 Jetty in the Victoria Basin. In the period 1940-41, during occurrences of Range-action, there were 15 occasions, out of 40 in which this berth was occupied, that ships parted ropes. In the period 1941-42 there were 5 occasions out of 39; in 1942-43, 7 out of 34, and during 1944-46, 3 out of 32. In all, over the entire period 1940-46, there were 30 occasions out of 145 - a percentage of 20.7. As all the other berths are analysed in this way for the same occasions, it is clear that the final percentages in the last column of the table are properly relative and may therefore be regarded as comparative indices of the susceptibilities of the different berths to effects from Range-action. As such, these percentages may be taken as the values of α , the berth or location factor introduced into equation (73). So long as the values of α are relative, as between different berths, it is of no consequence what form the figures take: they may even be regarded as weights applied to observations.

A study of the values of α for the different berths throws interesting light on the positions in the harbour that are best and worst from the point of view of Range-action. In the Victoria Basin the outside of No. 2 Jetty and the Elbow are the worst berths, followed closely by No. 3/4 South Arm. No. 7 Quay and East Pier are very much better, but still inferior to the remaining berths in the Victoria Basin. The north side of the Collier Jetty is undoubtedly the safest berth in the basin, and the inside of No. 2 Jetty ranks next

Table XIX: Relative Susceptibilities of Berths to Range-Action.

Basin	Berth Occupied	Ratio of Occasions of Rope Breakage to Occasions Berth Occupied				Totals	Relative Susceptibilities α %
		1940-41	1941-42	1942-43	1944-46		
Victoria	East Pier	11/39	3/41	0/35	2/27	16/142	11.3
	No.7 Quay	8/41	4/42	3/36	1/25	16/144	11.1
	Outside No. 2 Jetty	15/40	5/39	7/34	3/32	30/145	20.7
	Inside No. 2 Jetty	1/41	5/43	2/39	1/33	9/156	5.8
	North-side Collier Jetty	2/33	1/40	0/38	0/39	3/150	2.0
	South-side Collier Jetty	6/39	6/41	1/39	2/38	15/157	9.6
	No.1 So.Arm	8/40	4/40	1/37	0/31	13/148	8.8
	No.2 So.Arm	3/35	4/39	0/34	3/32	10/140	7.2
	No3/4So.Arm	9/37	11/42	3/37	3/29	26/145	17.9
	Elbow	13/39	10/42	3/37	4/29	30/147	20.4
	Totals	76/384	53/409	20/366	19/315	168/1474	
	Percentages	19.8	12.9	5.5	6.0	11.4	
Duncan	A	11/41	8/40	5/38	8/29	32/148	21.6
	B	17/43	13/40	11/38	6/23	47/144	32.7
	C	9/36	10/40	3/39	4/23	26/138	18.9
	D	9/28	9/39	5/37	8/24	30/128	23.5
	E	1/30	4/37	1/37	1/29	7/133	5.3
	F	3/23	1/37	2/38	2/28	8/126	6.4
	G	1/2	4/40	0/37	4/30	9/109	8.3
	H	-	5/23	1/41	4/27	10/91	11.0
	J	-	3/13	0/22	3/31	6/66	9.1
	K	-	3/9	1/32	0/21	4/62	6.5
	L	-	-	2/14	8/24	10/38	26.3
	M	-	-	5/21	2/9	7/30	23.3
	Totals	51/203	60/318	36/394	50/298	196/1213	
	Percentages	25.1	18.9	9.1	16.8	16.2	
	Grand Totals	127/587	113/727	56/760	69/613	365/2687	
	Percentages	21.6	15.6	7.4	11.2	13.6	

in order of merit. The values of α substantiate to a remarkable degree the general opinions held by nautical men as expressed in Capter III.

The values of α for the Duncan Basin show that H berth is rather worse than the adjacent berths, but that A, B, C and D berths are most prone to give trouble. B-berth stands out as unquestionably the worst berth in the basin, there being a 1 in 3 chance that trouble will be experienced there during Range-action. D-berth, while being better than B, is nevertheless worse than C, as also is A. All the berths A to D are bad, but the fact that C berth, at the node of the transverse seiche, is the best of the four provides interesting food for thought.

Here we venture to suggest that it proves that the second harmonic of the transverse seiche, with a periodicity of the order of 0.9-1.0 minute, is the main culprit in breaking mooring ropes. Berths B and D coincide very closely with the nodal positions of the binodal transverse seiche, and the node at B-berth would almost certainly curve round and abut on the middle of A-berth, thus accounting for the 1 in 5 chance of the latter berth giving trouble. These deductions dovetail admirably with the conclusions reached under Section 132 (p. 395), that it is oscillations of periodicity less than about 1 minute that are most critical for ships.

It will be noted from Table XIX that E-berth is relatively the safest in the Duncan Basin, and that from E to K the berths are very much better than at the north end of the dock. At L and M berths(Fig. 4), however, conditions become bad again. Particulars for the stub-berths along the Eastern Mole have not been included in the tabulation because it could not be certain from the records where exactly ships had been located: in any case, damage at the stubs was mainly to ships' plating and to fenders and therefore not in the same category as damage to moorings.

In passing, it is of interest to consider the totals for the individual columns of Table XIX. For instance, in the period 1940-41 there were 76 out of 384, on an average of 384/10 or 38 occasions of Range-action, that suffered fractured ropes - a percentage of 19.8 per occasion of Range. For the same period 51 ships out of 203 in the Duncan Basin parted ropes on an average of 203/7 or 29 separate occasions of Range-action - a percentage of 25.1 per occasion of Range. These percentages may be regarded as a general index of the severity of Range-action over the period. Comparison with the corresponding percentages in the neighbouring columns suggests a considerable lessening of the magnitude of Range-action in succeeding years, the period 1942-43 having been the mildest. The average figures for both basins given in the bottom row of the table are perhaps the best indices of the general trend. Table XVII (p. 388), which treated this data in a different way, uncovered the same general indications*.

Treating the results collectively over the entire period 1940-46, column 7 of Table XIX shows that there is an 11.4% chance of trouble somewhere in the Victoria Basin as against a 16.2% chance in the Duncan Basin. In the harbour as a whole there is a 13.6% chance of rope breakages occurring during Range-action. The relative susceptibilities of the two major basins are as 11.4 to 16.2, or as 1 to 1.42, which rates the Duncan Basin about half as bad again as the Victoria Basin.

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* In comparing Tables XVII and XIX, it should be noted that the column-totals in the latter table do not represent separate occasions of Range-action. Many of the occasions recorded in the columns were common to ships at different berths.

138. Statistical Analysis of Rope-Breakages.

The quantity on the right-hand side of equation (79) represents in a general sort of way, as we noted on p. 405, the statistical average damage at a berth caused by Range-action, making due allowance for the peculiar susceptibilities of particular berths (α), for the sizes of ships occupying them (W), and the number of ropes (N) used in mooring each ship. To discover how this quantity ($1/\beta$) was related to the magnitude of Range-action, A , a statistical analysis was undertaken in which individual values of $\left(\frac{W\alpha}{Nn}\right)$ were calculated for each berth where there was a record of broken ropes, and the sum of their reciprocals obtained for all the occupied berths in one basin to give values of β .

The tabulation of the data handled would be too voluminous to include here, and we may therefore illustrate the method followed merely by considering a typical row in the statistical table.

We shall consider first of all the Duncan Basin on the occasion of June 12th, 1940. At that time the Lege tide-gauge in the Alfred Basin showed $5\frac{1}{2}$-minute oscillations of amplitude $A=13\frac{1}{2}$, while the Lea tide-gauge in the Duncan Basin showed a longitudinal (4-6 min.) oscillation of amplitude $A=3$, ins. and a transverse oscillation (1.8 min.) of amplitude $A=9$ ins.

Only A, B, C, D, and E berths were occupied at the time, making $m=5$. Of the five ships, the 'Lanarkshire' ($W=17700$ tons) at C berth parted 1 rope and the 'Dumfries' ($W=12200$ tons) at E-berth 2 ropes. From Fig. 208, the number of mooring ropes each ship probably had was $N=18$ for the 'Lanarkshire' and $N=15$ for the 'Dumfries', while from Table XIX, the values of α for the two ships respectively are 18.9% and 5.3%. All the necessary data are now on hand to enable the products ($W.\alpha/N.n$) to be calculated for the five berths. For the two berths C and E the products are computed to be 186 and 22 respectively: for the other berths they are all infinity, since n , the number of ropes broken, is zero at each. In accordance with equation (79), we now compute $1/\beta$ as 1/5th of the summation of the reciprocals of these products, so that

$$1/\beta = \frac{1}{5}\left(0+0+\frac{1}{186}+0+\frac{1}{22}\right)$$

from which β is found to be 100. The meaning of the value can perhaps best be explained when we come to consider the results of plotting β against A.

In the Victoria Basin on the date we are considering, three ships parted ropes at East Pier, No. 3/4 South Arm and the Elbow; respectively the 'Glenorchy' ($W=19100$, $N=19$, $n=1$, $\alpha=11.3\%$), 'Indrapoera' ($W=17000$, $N=19$, $n=3$, $\alpha=17.9\%$), and 'Sarpedon' ($W=19000$, $N=19$, $n=3$, $\alpha=20.4\%$). At the time, nine berths were occupied, making $m=9$. The respective values of the products ($W\alpha/N.n$) for the three ships are 113, 169, and 68, whence

$$1/\beta = \frac{1}{9}\left(\frac{1}{113}+0+0+0+0+\frac{1}{169}+0+0+\frac{1}{68}\right)$$

and β is computed to be 300.

For the whole year of 1942 and half of 1943 the Lea tide-gauge records for the Duncan Basin were over-damped and failed to register the Range oscillations. In order that valuable data over this period should not be lost to the statistical analysis, an attempt was made to estimate the magnitude of the Range effect in the Duncan Basin from the magnitude of the oscillations in the Alfred Basin. Fig. 29, already presented (p. 133), established an approximate relationship between oscillations in the Alfred and Duncan Basins, using data for the remaining period between 1940 and 1946. The results are somewhat variable, but that an average relationship exists is clear from the disposition and density of the plotted points. The mean lines through the plotted points were therefore used for interpolating values of the amplitude, A, for the Duncan Basin during 1942/43.

The values of β, calculated on the lines described above, were plotted against the amplitudes, A, of transverse oscillation in the Duncan Basin and surge in the Alfred Basin with the results shown in Figs. 209 (a) and (b) for the Duncan Basin and Figs. 210 (a) and (b) for the Victoria Basin. Plotted points, whose amplitudes were interpolated from Fig. 29, are distinguished from the others so that their dispositions can be noted separately. As it turns out the separate sets of points, (white and black), completely support each other and independently would each give about the same result.

Of the nature of the general relationship between β and A reflected in Figs. 209 and 210 there can be no doubt. The statistical average relationship in every case is found to be hyperbolic, as predicted by equation (80), and the fact that it so evolves proves the general soundness of the arguments leading up to this method of analysing the data.

There is admittedly a considerable scattering of points, but not more so than would be expected from the nature of the data being treated. The scattering of plotted points may be attributed to any one, or all, of six factors, which may be listed as:

(1) The uncertainty of knowing the exact magnitude of the Range-action. (The average maximum has in general been taken, but often the maximum is of short duration).

(2) The manner of mooring of ships - whether ropes are tight or slack. (The importance of this aspect has already been stressed in Sections 132 and 133, ante).

(3) The number of ropes used to moor a ship - whether

adequate or otherwise. (There being no hard and fast rule as to the number of ropes to be used, a ship may perhaps have a deficiency of ropes at the critical time).

(4) The condition of the ropes - whether new or old. (Old ropes near the limit of their useful life may break under relatively mild conditions, thus giving perhaps a spurious importance to some data).

(5) The uncertainty regarding the actual displacement tonnages of ships. (A ship is usually in port for several days, during which time her draught can vary considerably according to her state of loading and unloading).

(6) The possibility that the magnitudes of the 1.8 and $5\frac{1}{2}$ min. seiches considered may not be adequate indices of the magnitudes of higher frequency seiches which are critical for ships. (The whole trend of the investigations of this chapter is to show that periodicities below about 1 minute are most dangerous for moored ships).

The assumption will now be made that if all these factors could be precisely controlled, the relationship between β and A would conform with the statistical average of all the points plotted as represented by the mean lines drawn in Figs. 209 and 210.

In Fig. 209 (a) values of β for the Duncan Basin have been plotted against the amplitudes of the transverse seiche in that basin: in Fig. 209 (b) they have been plotted against amplitudes in the Alfred Basin. Values of β for the Victoria Basin have been similarly plotted in Figs. 210 (a) and (b). It appears that whether effects are judged by the measure of Range in the Alfred or the Duncan Basin, the result is much the same. When amplitudes are about a quarter of the maxima recorded, values of β become large in all cases and the chances of rope-breakages almost vanish. This result answers at once the question we posed at the start of this analysis (Section 135, p. 401) - by how much must oscillations in the existing harbour be reduced by any proposed solution in order to yield complete safety for shipping?

139. Diminution of Range Necessary for Immunity from Damage.

By ensuring that amplitudes are reduced to 25% it will be reasonably certain that on the statistical average ships will be immune to rope-breakages. This does not, of course, mean to say that breakages will not sometimes occur: there will always be freak cases similar to some of the scattered points to the left of the curves of Figs. 209 and 210.

It may be shown that a reduction of amplitude to only 50% would be inadequate to give satisfactory protection to shipping. Figs. 209 and 210 show that the values of β corresponding to a reduction of amplitude to 50% of the maxima are 235, 180, 235 and 235, or, say, 220 as a mean of the four curves. If we assume for convenience that a basin is occupied by ships all of one size and that the berths are all equally susceptible to effects from Range-action, then equation (79) may be transformed to

$$\sum_{1}^{m} n = \frac{m.W.\alpha}{N.\beta}, \qquad \text{(81)}$$

giving the total number of ropes broken.

Assuming that only four ships are using the Duncan Basin at berths A, B, C, and D, whose average susceptibility to Range action from Table XIX is 24.2%, and that the ships displace 20,000 tons and are each held by 20 mooring ropes, then equation (81) shows that for β=220, 4 ropes will be broken on the statistical average. Remembering that on this basis ropes break only through being genuinely overloaded as a result of the severity of the Range-action, it is clear that the 50% solution is not satisfactory.

There remains, however, a further consideration to influence our judgement in this matter, and this is a statistical examination of the damage at the stub-berths along the Eastern Mole. This damage has comprised, almost entirely, crushed floating fenders and dented shell-plating, and it is obvious therefore that the movement of ships at the stubs is mainly off-and-on and therefore broadside-on to the seiche.

Now it can be shown that the maximum pressure which a ship of beam $2Y_0$ will exert on the fenders of a quay wall, when the clearance between itself and the fenders exactly equals the amplitude of an off-and-on movement from a transverse seiche, is [*]

$$P_{max} = 2\pi^2 m^2 W.\left(\frac{Y_0 A}{B^2}\right) \qquad \text{———————(82)}$$

Here m is the nodality of the transverse seiche and B the width of the dock across which it oscillates, A being, as before, the amplitude of the seiche and W the displacement tonnage of the ship. Since the dimension of a ship across the beam is linearly related to its displacement tonnage by an equation of the form

$$Y_0 = C_1 + C_2 W$$

C_1 and C_2 being constants, equation (82) becomes

$$P_{max} = \frac{2\pi^2 m^2 A W}{B^2}(C_1 + C_2 W) \qquad \text{———————(83).}$$

For a given basin the pressure is therefore greatest for a seiche whose nodality and amplitude are such as to make m^2A a maximum. A binodal seiche (m=2) whose amplitude A_2 is more than one-quarter of the amplitude A_1 of the fundamental seiche will thus give a greater force of impact. A trinodal seiche (m= 3) of amplitude greater than $A_1/9$ or more than $4A_2/9$ would give the worst effect, and so on. Equation (83), it must be stated, is not valid for values of m much larger than

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[*] L.c. (Ante p. 292), [123], pp. 18-21.

3 or 4, but since the amplitudes of seiches, of nodality higher than this, usually decay very rapidly, this is not a serious drawback.

The conclusion may be reached that seiches between say 1 minute and 20 seconds will be most dangerous for ships in lateral impact, since these are the most active multi-nodal seiches within a harbour. Further, the mass of the ship, as will be seen from equation (83), is of paramount importance in lateral ship motion, especially as the impact force increases as the square of the displacement tonnage in the second term of the expression.

Upon this theoretical background a somewhat similar analysis to the one for rope-breakages in Section 135, which for the sake of brevity we omit from this record, leads to the result shown in Fig. 211. Here despite a wide scattering and paucity of points, the theoretical trend is again established, and, moreover, the curve shows once more that on the statistical average, if seiche amplitudes are reduced to about 25% of the possible maxima (about 10 ins. for the transverse seiche in the Duncan Basin), the chance of fenders being crushed becomes exceedingly remote.

It was on this basis then that the criterion, that a real solution of the Range problem must reduce the present-day maximum effects by 75%, was adopted as a guide in the model experiments described in the last chapter (cf. p. 383).

140. The Cause and Prevention of Damage from Range-Action.

We conclude this chapter with some general observations and conclusions on the question of ship response to Range-action.

The fore-and-aft, off-and-on and up-and-down gyrations of ships during Range-action are essentially the result of the mass-movements of water caused by seiches within the harbour basins. Under the stimulus of this disturbance and the reaction of its own ropes, a ship may develop a resonant oscillation in longitudinal motion which may impose excessive strains on the mooring ropes, leading to fatigue and fracture.

The theoretical concept that a ship behaves much like a spring-suspended mass, that is agitated by some impressed periodic force (Section 133, p. 392), has been confirmed experimentally (p. 401), statistically (p. 412) and observationally (Table XVIII, p. 390). The conditions which are likely to develop resonance between ship movement and sea oscillation really depend on the size of a ship and the manner of its mooring, and upon the magnitude and periodicity of the sea-oscillation which constitutes the impressed force.

Each ship according to her size and the degree of slackness and other characteristics of her moorings will have a certain inherent critical periodicity of oscillation. If this disagrees with the seiche-periodicity resonance is impossible, and no serious consequences will ensue. This appears to account for the fact that certain ships successfully ride out quite severe occurrences of Range-action, when others, whose rope-spring systems are more consonant with the impressed surges, are violently set in oscillation under comparatively mild Range conditions.

It would appear that for the average size of ship calling at the port of Cape Town, the dangerous periodicities at which resonance is possible are below about 1 minute (pp. 393, 395, 416). This result, derived theoretically, is confirmed observationally (p. 390), and statistically (p. 408), and may be further supported by a simple process of induction.

We have already noted (pp. 300, 312) that at periodicities above about 4 mins. only a general rise-and-fall of water occurs over the entire area of the Victoria Basin. Such motion is clearly incapable of stimulating longitudinal ship motion, and we conclude at once that critical periodicities for ships must be less than 4 minutes. We may go further than this however, for in the periodograms of Fig. 124 (b) for the Victoria Basin we note that the critical bands of oscillations below 4 minutes are 2.3-2.4 minutes and 1.5-1.9 minutes, of which the latter is much the stronger. We are thus able to infer that since (from Table XIX) the Victoria Basin has fully (11.4/16.2) or 70% of the susceptibility of the Duncan Basin to range damage in the form of broken ropes, critical periodicities for shipping must be less than 2.4 minutes, and probably less than 1.9 minutes. If the latter periodicity was the trouble-maker we could expect the north side of the Collier Jetty and the inside of No. 2 Jetty to be fairly bad berths, for model tests show this area of the Victoria Basin to be sensitive to periodicities of the order of 2 minutes. Table XIX, (p. 407), however, shows that these berths are the best in the dock, and the conclusion must therefore be that the real disturbing agents for ships are seiches of still higher frequency, which are less easily able to penetrate into the inner sanctums of the Victoria Dock.

While most ships appear to be dangerously responsive to large amplitude seiches of periodicities below about 40 seconds (p. 393), feeble resonance is possible with small amplitude seiches of much greater periodicity. It is possible therefore for the critical motion of a ship to comprise several degrees of resonance from a number of superimposed seiches, the lower modes of oscillation contributing in a small way to the total critical effect.

Tight moorings are a fairly successful antidote to Range troubles, provided that the amplitudes of high frequency disturbances are small, and provided all slack in the ropes can be properly taken up. In practice it appears to be almost impossible to achieve this desirable condition in the first instance, let alone maintain it in the face of the tidal fall. Tight ropes, moreover, while effective against longitudinal ship motion, have very limited control on lateral motion, which is really much the more serious feature of Range action (p. 416).

It would appear from the studies presented in this chapter that almost complete immunity from the troubles of Range-action can be secured at Cape Town by damping the magnitude of present-day effects by some 75%. This degree of subjugation (and more) has been shown in the model experiments to be attainable with the form of outer basin illustrated in Fig. 191.

CHAPTER XVII.

THE PREVENTION OF RANGE DISTURBANCE.

> " ....the power of man over Nature is limited only by the one condition, that it must be exercised in conformity with the laws of Nature".
>
> —— Sir John Herschel,
> Discourse on the Study of
> Natural Philosophy, (1851).

141. Recapitulation.

The general peculiarities of the Range phenomenon have now been described in some detail in earlier parts and chapters of this work. Individual summaries of various aspects of the studies on this problem may be found within preceding pages as follows:

I.	The Phenomenon of Range (as a troublesome feature of the harbour at Cape Town, and as it was locally understood)	Introduction. (pp. 3-8); Section 20 (pp. 59-61).
II.	The Phenomenon of Range (as a universal occurrence in Nature, and as it was understood in other parts of the world).	Section 43, (pp. 126-128).
III.	The Origins of Range (as deriving from artificial, seismic and meteorological disturbances of the sea).	Section 78, (pp. 223-230).
IV.	The Mechanism of Range (as uncovered by observation, measurement, theory and experiment.	Section 103, (pp. 303-313).
V.	The Action of Range on Shipping (as found from observation, measurement, theory and experiment).	Section 140, (pp. 416-419).

There remains to consider the ways and means whereby the Range phenomenon can be controlled for the protection of shipping in the harbour at Cape Town, and to gather what seeds of wisdom, if any, may be winnowed from the researches. Before so doing, however, we may, for the purposes of further discussion in this chapter, briefly review what has now been gleaned.

142. Origin of Range-Action.

Range-action has been shown to arise from the incidence of long ground-swells on the western and southern coasts of South Africa, arriving from sources in the south-western ocean.

The phenomenon has now been correlated with the passage of frontal depressions across the South Atlantic. In this region vast atmospheric vortices form between the warm equatorial and cold polar air-masses over the open ocean. The resulting depressions travel in general on a south-easterly course at speeds of from 30 to 40 knots, passing, usually, far south of Cape Town. Violent winds blow clockwise round the depression-centres, their velocity increasing towards the kernel of the storms in proportion as the barometric-gradient increases. The depressions, however, cover enormous areas and their prominent cold-fronts, which are surfaces of discontinuity between the warm and the cold air-masses, stretch in crescent formation over distances of 1000 to 1500 miles north of the centres.

Along the line of the cold-front cold air is continuously boring in under the warm air-mass, as the whole formation progresses. It is the arrival of the antecedent warm air and of the following cold fronts that brings to Cape Town its north-westerly and westerly winds, its winter storms and rain, and finally its sea-swells and Range-action.

Within the storm-areas waves are whipped up by the winds, the most prominent periodicities of the waves being proportional to the wind-speed. The wave-trains of longest periodicity and greatest amplitude thus tend to originate near the storm-centre and propagate with the greatest amount of energy.

It would appear that the surface-traction of high winds is capable of generating waves of periodicities up to a limit of about 25 seconds. Waves of periods of 15 seconds and more are probably assisted in their development by barometric fluctuations which increase with the wind-speed and take over the work of imparting energy to water in the form of longer waves (periods exceeding 25-30 seconds), when surface-traction of the winds is no longer adequate for the task.

Besides the wind-traction/barometric-fluctuation source of sea-waves and ground-swells, it has been shown that a train of wind-waves, passing clear of wind-domination and free to propagate as a smooth procession, will of its own accord develop antecedent and sequent ground-swells through its natural tendency to attenuate.

A third source of ground-swells may lie in the collapse of a travelling depression through dissipation in the face of high-pressure anticyclones. Ground-swells in this case would arise from the gravitational flow of the released head of water under the depression centre.

Exceptionally long forced sea-waves can be generated by long-period air-waves or barometric fluctuations, which appear to arise when one depression overtakes another.

143. Nature of Range-Action.

The sea-waves and ground-swells eventually roll into

Table Bay. They may be brought in on the teeth of the wind with rain and sleet when the cold-front of a depression crosses over Cape Town, or they may arrive in clear, calm weather from remote distances in the South Atlantic.

The energy of the highest frequency waves (periods less than 15 seconds, say) is largely destroyed through turbulence and vorticity in the surf along the coast, but the longer ground swells merely surge up the shore without breaking and reflect to form standing waves with oncoming members of their trains.

Where the topographical features of a bay, inlet or semi-enclosed basin favour it, the underlying ground-swells are repeatedly reflected and form resonant oscillations or seiches. The basin selects for this purpose only those of the incident waves as have about the same periodicity as its own natural periods of oscillation.

The whole phenomenon may be represented by the analogue of a bell and a series of tuning-forks, of which the bell represents Table Bay and the tuning-forks the train of waves. If a tuning fork is vibrated and held in the hollow of the bell without touching any part of it, there will be no obvious result so long as the frequency of vibration of the fork is in marked disagreement with the frequency at which the bell itself would normally vibrate if struck. But when the right tuning fork is selected, the response is instantaneous and the bell gives forth a clear audible note.

The special property of a seiche consists in a synchronous movement of the entire water-mass of the bay or basin, in which every water-particle moves in phase with every other. The seiches tend to be uninodal or multinodal by oscillating about one or more nodes where water-particle movements are horizontal only. The essential mechanism may be understood from the water movements which quite ordinarily occur in a bath-tub once a disturbance has been created and the water is allowed to quieten down. After the small disturbances have damped out, the water will be found to rise and fall rhythmically at opposite ends of the bath and to move only horizontally at the centre. Such an oscillation would be described technically as a uninodal seiche, through having but one node across the centre of the bath. Binodal and multinodal oscillations may sometimes be recognised coexisting or superimposed upon the fundamental seiche.

Evidence has been adduced to show that even the South Atlantic Ocean itself performs slow molar perturbations under the influence (apparently) of the travelling depressions, the oscillations taking place between the mid-Atlantic ridge and the west coast of Southern Africa. Certain of the higher harmonic oscillations of this gigantic basin are able to resonate in the bowl of Table Bay, and classify as forced seiches. Forced seiches are oscillations which through being resonant in some external system are impressed upon an internal system, such as Table Bay in this case, in which they may or may not be resonant as well.

Of its own accord Table Bay is able to respond to frequencies of disturbances which are too high to produce any effect upon the greater oceanic basin. The bay has been found to function very much like a composite of an ellipsoidal, circular and rectangular bowl, and has natural modes of oscillation peculiar to it. The most prominent periodicities, among many others, are 62, 51, 33-26, 23-17, 14-12, 11-10, 9.8-9.4 minutes.

In the same way that the forced seiches of the oceanic basin influence Table Bay, so the forced seiches of the bay are impressed upon the quasi-basin formed between the breakwater and the shore. As it chances, the 11-10 minute seiche for the bay is exactly resonant for the breakwater-shore system, while the 14-12 and 9.8-9.4 minute forced seiches are near-resonant.

Quite apart from this, the breakwater-shore quasi-basin begets its own natural seiches of higher frequencies to which the bay is largely insensitive, and these in turn become the forced seiches to influence the harbour-basins.

The troubles of Range-action peculiar to Table Bay harbour arise from the excitation of seiches within the docks which are sympathetic to the forcing seiches in the external roadstead. By an odd mischance the dimensions of the Duncan Basin and the location of its entrance favour the development of longitudinal and transverse seiches of the same periodicities as some of the harmonics of the breakwater-shore oscillating system. Not unnaturally the oscillations within the harbour basins are able to attain appreciable magnitudes.

For the Duncan Basin, which is almost exactly rectangular, the natural periods of longitudinal and transverse oscillation, in the fundamental (uninodal) modes, are respectively of the order of 5.6 and 1.8 minutes. For the Victoria Basin which is roughly square the fundamental oscillation is about 1.9 minutes. If we double the longest periodicity for each basin, we obtain a mode of oscillation in which the node is at the mouth of the basin and the antinode at the far end of the dock, most remote from the entrance. For the Duncan and Victoria Basins this condition obtains at periodicities of about 11 and 4 minutes respectively.

All forced seiches of periods greater than these respective figures act on the basins as surges through the entrances, which create a general rise and fall of water over the entire dock areas. Thus the 33-26 and 23-17 minute seiches of the bay impress themselves upon the harbour basins in this way, while many of the seiches of the breakwater-shore system which have periods greater than 4 minutes impose themselves in like manner on the Victoria Dock.

All seiches of periods less than 4 minutes in the Victoria Basin and 11 minutes in the Duncan Basin constitute oscillations about nodes within the basins, and these are the ones which are ordinarily referred to as Range. We may thus recognise two kinds of action that can take place, either singly or together, depending on the forcing seiches in existence. An oscillation may develop inside a basin and be sustained with relatively feeble transference of water through the basin mouth, or a comparatively slow rise and fall of water over the entire dock area may take place, accompanied by a powerful flux of water through the basin entrance. The first kind of action is dangerous to moored ships while the second is dangerous only to ships being navigated through the dock entrances.

144. Ship Response to Range Action.

Internal oscillations in a basin affect ships by causing them to move longitudinally, laterally and vertically, sometimes with a roll, wherever a ship may happen to lie in the periodic (reversible) currents of the oscillation. Ships resist these movements by pulling on their mooring ropes or making contact with the floating fenders, but as the forces to be countered comprise the inertia of the ship and the pressure of the surge, (which, in effect, doubles the inertia of the ship), it is easy to see how damage can result when large ships are involved.

In longitudinal motion along a quay a ship can resonate with the activating seiche provided its moorings are of the right order of slackness. It has been found from theoretical principles, verified by experiment and confirmed by actual measurements on ships, that the most dangerous conditions for ships as ordinarily moored prevail when seiches with periods of the order of 1.2 minutes and less attain large amplitudes in the harbour basins. It is known that second and third harmonics of the fundamental transverse seiche (1.5-2.1 mins.), respectively of periods 0.8-1.1 and 0.5-0.7 min., can attain considerable prominence during severe Range-action, particularly in the Duncan Basin. To the action of these high-frequency seiches must therefore be attributed much of the troubles that have arisen from ships breaking adrift.

It has been shown that the size of a ship is not of the importance in longitudinal ranging that might be expected. Far more important are the magnitude of the seiches and the condition of the moorings. Large ships, however, tend to resonate at somewhat longer periodicities than smaller ships, but even for the largest ships it is still the multinodal seiches that are most critical. This, of course, is not to say that the effects of the prominent transverse seiches (1.5 - 2.1 mins) are negligible: these, undoubtedly, contribute to the total effect of causing a ship, ultimately, to overstrain its ropes.

In lateral motion off and on a quay, a ship is, strictly speaking, unable to resonate, because the latitude for movement is far greater than the extent of surge and the essential spring-system is lacking. Nevertheless, if a ship happens to be off a quay by the right amount when an on-surge takes place, the forces of impact at the end of the movement, when acceleration is a maximum, can be very great. The mass of the ship is of the greatest importance in this case for the force of impact (in part) is proportional to the square of the displacement tonnage.

As the greatest accelerations in the off-and-on movement are caused by the prominent multinodal seiches, the inference can again be drawn that it is periodicities of about 1 minute down to say 20 seconds that are most critical for ships.

A factor of considerable importance governing the behaviour of a ship during Range action, depends upon the location within the harbour where it happens to be berthed. Some berths are worse than others according to the disposition of the nodes and antinodes of the various seiches: as the latter are largely invariable, it is possible to define the relative susceptibilities of the different quays. This has been done statistically in Table XIX (p. 407) with very interesting results which are confirmed without exception by the personal observations of the Port Captain and his staff.

The worst berths in the harbour are along the Eastern Mole where off-and-on action is very strong, but the stub jetties are partly to blame for the notoriety of this part of the harbour, owing to their effect in holding ships farther off the real boundary wall of the Eastern Mole than is desirable. In consequence, ships, berthed across the ends of the stubs, are subject to larger lateral displacements and accelerations than would otherwise be possible were they tied along a straight quay wall.

Of the remaining berths B in the Duncan Basin ranks as the worst, with a 1 in 3 chance that ropes will be fractured there during an occurrence of Range-action. Several other berths in the Duncan Basin are also bad, as also are two or three in the Victoria Dock (cf. last column of Table XIX, p. 407). Generally, however, the Duncan Basin shows a greater propensity for Range troubles than the older dock, and this can be ascribed very largely to its greater size and the smaller degree of protection it receives from the breakwater as well as to its unfortunate dimensions in relation to the external dimensions of the harbour, and the position of the latter in relation to the bay.

Over the years 1940 to 1946 there was a notable lessening of the magnitude and frequency of the Range disturbances at Cape Town, which seems to have persisted up to the present time. It is likely that this trend is related to secular changes in the weather operating upon the travelling depressions of the South Atlantic. In the worst years of Range-action (1940-1942) there were about 40 occasions per year when Range action was severe enough to cause rope breakages and other damage. By 1945-46 this frequency had dropped to about 15 occasions per year, and in more recent years it may have decreased further, although this has not been specifically checked.

The second type of action, which we noted as affecting only the navigation of ships through the basin entrances, does not ordinarily reach troublesome proportions concurrently with the first type of action, (involving ship ranging), except in the Victoria and Alfred Basins. In these two basins surging at the mouths can be very unpleasant during severe Range-action, as a result of forced seiches with periods from 4 to 12 minutes, but it requires seiches of longer periodicities than this to create the equivalent effect at the mouth of the Duncan Basin, and the forced seiches of the bay, which do it, are not usually at their worst when strong Range-action of the first type prevails.

The long-period seiches of the bay have been found to reach large amplitudes under the influence of prominent air-waves or barometric fluctuations, simultaneously with their crossing over Cape Town. The effect of these seiches upon the Duncan Basin is to cause a violent flux and reflux of water through the entrance at velocities up to 4 or 5 knots, often persisting intermittently for as long as 2 or 3 days. The phenomenon has been found to occur as often as 10 to 15 times a year, and to reach really dangerous proportions on perhaps 2 or 3 occasions per year.

While collisions of ships with fixed structures have been narrowly averted at the Duncan Basin entrance, they have several times occurred in the more confined spaces of the Victoria and Alfred Basins. As the spate of the reversible currents can destroy the momentum of a ship and whisk her out of control like flotsam, it is always potentially dangerous.

145. Requirements of a Complete Solution to the Range Problem.

The ideal solution to the Range problem would be one which not only reduced the internal oscillations in the harbour basins to harmless proportions and eliminated dangerous currents from the entrances, but left the port as free and untrammelled as the efficient conduct of its services requires. The solution must be such, moreover, as to cure the Range troubles without raising any fresh problem, engendered by its application.

It must be admitted at the outset that such an ideal solution is unattainable for the reason that there is no known method of combating the currents in the basin entrances, short of sealing them off entirely.

It is axiomatic that the lower the frequency of a wave or seiche, the less chance there is of blocking its entry into a confined area. Thus no harbour construction, short of a lock-gate, can ever subjugate the tidal flux. At the other end of the scale, the highest-frequency waves, as we know, can be shielded from an open roadstead by a simple breakwater.

These extremes can be regarded as special cases of a general theorem that

> The width of entrance necessary to exclude serious wave disturbances from the interior of any basin depends on the frequency of the disturbance, being theoretically infinite for the highest frequency waves and zero for the lowest frequency waves.

The form of this relationship is not difficult to envisage and might perhaps be expressed mathematically as

$$b = kp^{n} \qquad \text{\_\_\_\_\_\_\_\_\_\_(84)}$$

where b is the entrance width, p the wave-frequency, k a constant and n a numerical exponent. Although this theoretical concept is very imperfect and largely of academic interest it may serve to guide us in the practical issue. The equation satisfies the extreme conditions we have postulated, and further allows for the observational fact that a basin entrance would have to be practically nothing at all to choke fairly low frequencies of waves (small values of p).

For the purposes of argument, we may rewrite (84) as

$$b = k\tau^{-n} \quad ,$$

where τ is the wave-period, and select an arbitrary value of n , say 2. If the Duncan Basin with an entrance width of 400 ft. is reasonably proof against 10 second waves, the constant k would have a value of 4×10^4 . Using this value of k we may now seek to enquire what entrance width would disperse 60 second waves. The answer is found to be 11 ft. This example will serve to illustrate our point that the degree of choking which is effective against long ground-swells, obtainable by a simple reduction in the entrance width of a basin, (within the practical limits possible), is extremely limited.

A specific example of this is afforded by the Duncan

Basin, the entrance-width of which was originally 750 feet. Although this mouth was subsequently narrowed by the very substantial amount of 350 feet, the narrowing failed to exclude the troublesome ground-swells, although it had a limited beneficial effect in masking the higher frequency waves. Even the Victoria Basin with an entrance only 250 feet wide, in the lee of the breakwater, is not proof against 60-second waves and lower frequencies (cf. Table IV, p. 257).

We have, therefore, to recognise the impossibility of controlling the currents of the very long period seiches. The best that can be done about them is to ensure that ships are safeguarded against damage in the event of their being carried out of control.

The position is more hopeful in the case of the internal oscillations within the basins, deriving from seiches of periodicities of less than, say, 6 minutes. The researches have shown (Section 139, p. 414), that if these are by any means reduced to 25% or less of the maximum magnitude known to have occurred in the worst years of Range-action, then ships are reasonably sure to be protected against damage. Any solution which accomplishes this will be a real solution though not a complete one.

As an alternative to the solution which seeks to eliminate the internal oscillations, is the solution that seeks to tolerate them, but at the same time immunize shipping from damage. Model experiments and theoretical considerations have shown that if only ships can be moored always with taut ropes, the chances of damage in longitudinal motion almost disappear. Any mooring technique which ensured permanently tight ropes, coupled with the use of shock-absorbing fenders, would therefore provide a solution to the problem without requiring the eradication of any essential features of the Range-action.

There would be need for considerable caution in embarking upon a solution involving additional sea-defence works lest the balance of natural forces already existing should be drastically upset, thereby creating new problems. One such potential problem at Cape Town is the erosion of the Milnerton foreshore. There are those who hold the view that the construction of the breakwater precipitated this erosion in the first instance, and that it has since been accelerated by the enclosure of the Duncan Dock. A solution of the Range problem which still further encroached on the sea spaces flanking the Milnerton shore, might easily aggravate this erosion. The exercise of due caution would therefore seem to be necessary, particularly now that precise measurements of the erosion have been made by the Municipality of Cape Town for more than a decade.

146. Possible Forms of Solution.

We proceed to consider specifically the types of solutions which might be applied to the Range problem in general and to Table Bay harbour in particular.

Many suggestions were received from interested persons at different times during the course of the research. They included such impossible and unpractical ideas as breakwaters to Robben Island, canals to False Bay, shoals in Table Bay, the use of air-jets to oppose the currents and break up the ground-swells, and finally the use of floating breakwaters. In respect of the last-mentioned, it is interesting to record that Scott-Russell* provided us with the answer fully a century ago:

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* Cf. Stevenson, (l.c. ante p. 11), [5], p. 79.

> Large floating masses would, certainly, intercept oscillating waves of a small depth, and in moderate weather they would often still the water.... No known force could effectively secure a large floating breakwater broadside-on to a heavy ground-swell. It would move horizontally with the wave of translation, which would propagate itself along the bottom, just the same as if the breakwater was not there.

Those suggestions which remain, or which evolved in the course of the researches at Cape Town, as being in any sense worthy of consideration, may be listed below as:

1. <u>Devices to enable ships to outride Range action without damage, ensuring</u>
    - A. Permanently tight ropes.
    - B. Prevention of lateral impact.
2. <u>Structural changes to the harbour</u>, reducing internal oscillations to harmless proportions.
    - A. Entrace gates or locks.
    - B. Re-location of Duncan Dock entrance, and/or internal piers.
    - C. Outer basin enclosures.
3. <u>Devices to permit safe navigation of basin entrances</u>.
    - A. Shock-absorbing protection at entrances.
    - B. Warning apparatus.

147. Solutions of Type 1A (Permanently Tight Ropes).

The problem of ensuring tight ropes at all times in the mooring of ships bristles with difficulties. The port authorities have many times stressed the practical difficulties which militate against the attainment of tight moorings. These include such factors as the efficiency of the ship's crew and their knowledge of the Range-conditions, the machinery available on the ship for hauling in ropes, and especially the state of the tide at the time of mooring. Added to this is a seaman's innate feeling that it is always essential to provide slack in the ropes when mooring at low tide in order to prevent their being overloaded at high tide. This outlook might be justifiable at some ports where the tidal rise is considerable, but at Cape Town where the range is not ordinarily greater than 5 feet it is unimportant. The inevitable result of this attitude is usually a rather too generous allowance of slack in the ropes.

Even conceding the most favourable combination of circumstances it is not practically possible to ensure tight ropes to the extent necessary to prevent play of a ship in the periodic currents of a seiche; at least, not while mooring technique remains what it is. If therefore, a solution to the Range problem is to be sought in the form of prevention without cure, it will be necessary to adopt some foolproof system of mooring which will ensure tight ropes at all times under all conditions.

One obvious method of accomplishing this, which comes to mind, would be to loop guy-wires round the bow and stern moorings of a ship and to apply lateral pulls on these ropes, (by running the guy-wires round capstans on the quay), sufficient to take up the slack in all the ropes. Any such system is, however, impracticable of adoption at Cape Town, owing to the confined working spaces between the crane-rails and the coping-edges of the quays. In any case, the desired result might be difficult to achieve owing to the fact that a group of bow or stern ropes, moored to a single bollard or several bollards, are non-parallel and widely dispersed.

One other method remains, which is not beyond the bounds of practical possibility, though not at Cape Town. It is mentioned here as a generality.

It envisages the use of specially designed 'pendulum bollards', as shown in Figs. 212 (a) and (b). These bollards would, in point of fact, be pendulums mounted on gimbals in steel frameworks, anchored to the quay wall. In general appearance the bollards would not be greatly different from ordinary fixed bollards common to most ports, for the gimbal suspensions and the main pendulum masses would be hidden from view under deck-plating. Fig. 212 (b) suggests the general form of the mechanism thus concealed.

In principle the operation of mooring a ship to the pendulum bollards would be briefly this. At the particular bollard to which the main bow or stern ropes of the ship were to be attached, a cover plate would be removed from the deck-plating and a portable lever used to operate a train of gears so as to cant the pendulum away from, or the bollard towards, the ship. The ship's ropes would then be secured to the bollard in the usual way and drawn as tight as possible by the usual means. Thereafter, when both bow and stern moorings had been made fast in this way, the gear-trains would be reversed until the pendulum masses exactly balanced the rope tensions. The gears would then be disengaged, and the pendulums would be free to react against the tendencies of the ship to displace longitudinally or laterally. By having two-axial gimbal suspension as shown in Fig. 212 (b), the pendulum would automatically align itself with the resultant of the rope pulls, but its direction of tilt would only be slightly oblique to the quay. Once the pendulums were released the slack in the ropes would be permanently taken up (Fig. 212 (a)), and violent and sudden strain of the ropes prevented in an subsequent movement of the ship.

Complementary to any such system of mooring would be the necessity for tightening the ropes again at low tide, and probably the abandonment of coir springs to prevent undue stretch and consequent sag of the ropes. The pendulum bollards themselves would act as shock-absorbers or springs, and the use of strops would be redundant. It is, of course, implicit in such a mooring scheme that any one bollard should not carry the mooring ropes of more than one ship.

148. Solutions of Type 1B (Prevention of Lateral Impact).

In the presence of severe Range-action of the off-and-on type damage can only be prevented by suitable shock-absorbing devices to cushion the impacts.

One comparatively simple and reasonably effective remedy, which has been regularly employed by the Port Captain at Cape Town in the last several years, uses anchors to hold a ship off a quay so that contact is impossible. The apparent objection to the general adoption of this practice is the danger of the anchor chains fouling other ships or craft using the harbour basins. It is also somewhat doubtful whether in really severe Range-action the system will continue to give success.

A more satisfactory answer to the impact question would be the employment of some sort of resilient fenders. Such fenders would be useful at all times whether other means were adopted to cure Range-troubles or not, and this fact is sufficient justification for examining certain possibilities in this direction.

A spherical pneumatic fender has been suggested by Mr. H. S. Olive, former Harbour Engineer, Port Elizabeth, and envisages use of a rubber sphere, pneumatically inflated, about 6 feet in diameter, as a buffer between ship and quay. The idea appears good though fraught with practical difficulties. Thus the point of attachment of the holding chain would come in for some very severe treatment, if, as will surely happen, it is rolled into contact with the ship or quay. The rubber will in course of time be lacerated by the chain under this action. The life of the rubber might not be very long anyway, owing to the severe stresses it would be subject to in being rolled as an oblate spheroid under compression.

A vertical suspended fender has been used with some success at certain British ports*. The device consists of a heavy vertical concrete cylinder, with timber facing, suspended by links to cantilever extensions from a quay wall. The arrangement of suspension is such that under pressure the cylinder yields horizontally and then vertically, and energy is absorbed in raising the heavy mass. A number of such vertical fenders, strategically placed along a quay frontage would no doubt very successfully eliminate all impact and prevent any damage to ships.

Another device which has the advantage of being transportable and usable in the same way that floating fenders are now employed is here suggested as a third possibility in this field. The arrangement is shown in Figs. 213 (a), (b) and (c), of which (c) is a photograph of a rough working model, built to demonstrate its feasibility.

The fender may be seen to consist of two sections, connected in parallellism by sets of links. The two sections of fender are held apart from each other by three powerful shock-absorbing springs of the type shown in Fig. 213 (b). As pressure is applied to the fender the sections come together under the action of the links and the contraction is

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* Suspended Fenders and Dolphins', Engr., Vol. 181, March, 1946 [124], pp. 221-222.

resisted uniformly by all three springs.

The spring mechanism is an adaptation of the 'Monarch' shock-absorber spring which is regularly in use at many ports, usually as a fixed or swivelling installation on quays for holding ships' ropes. Unlike the Monarch spring which uses the lever principle with fulcrum between the load and the spring-force, (Fig. 214) the spring arrangement of Fig. 213 (b) has the load intermediate between fulcrum and spring-force. As in the Monarch spring the fulcrum of the fender spring is arranged to displace towards the load as the load increases in magnitude, and because of the powerful leverage thus afforded, the helical spring is capable of carrying theoretically infinite load. Compression of the spring thus yields increasing resistance to the load and the shock pressure is smoothly absorbed. The spring mechanism of Fig. 213 (b) is mounted on pivots so that swivelling action is possible to compensate for the slight relative longitudinal displacement of the two sections of the fender.

As shown in Fig. 213 (a), the spring mechanisms could be housed in weather-proof covers above sea water-level by way of protection from the worst effects of flying spray. The relative displacement vertically of the two sections of the timber fender would be resisted by the torsional strength of the links, as also would be relative tilt. The sections would thus have limited freedom in only two directions, longitudinal and lateral.

It is estimated that a floating timber fender of this kind, of about the usual dimensions (say 50 feet long), would carry the load of the spring mechanism quite easily and stably. No more than the usual number of fenders (two) would be required at each berth.

149. Solutions of Type 2A (Entrance Gates or Locks).

One obvious solution to the Range problem, which appeals to many minds, is the provision of gates or locks at the basin-entrances. Either of these schemes is probably feasible, but both must be considered as serious impediments to the harbour.

Any kind of approach lock to the Duncan Basin would have to be built as far as possible in the direction of the wind: unless lined with shock-absorbing fenders it would always be a hazard to ships and a serious bottleneck to the harbour.

Much the same disadvantages attach to the provision of entrance gates. Here a considerable engineering problem would be posed in providing gates to operate successfully across wide gaps. The feat could perhaps be accomplished by means of retractable telescopic gates operating on rails on prepared sills, but the forces they would be called upon to resist would be enormous and the designs would have to be of extremely heavy build. The disadvantages, high capital cost and heavy maintenance expenses, in the author's opinion, rule out these schemes as practical solutions to the Range problem.

150. Solutions of Type 2B (Re-location of Dock Entrances, Piers, etc.)

Strenuous efforts were made in experiments on the model of Table Bay Harbour to find a solution to the worst features of Range-action, which would be relatively simple and inexpensive. The studies of the characteristics of seiches between the breakwater and the shore (pp. 273, 281) raised the hope that a new position might be found for the Duncan Basin entrance which would make that dock less susceptible to the stimulus of the external seiches. At one stage this search looked very promising (cf. Section 127, p. 377), but more rigorous and comprehensive tests, undertaken later, revealed that no simple solution of the problem apparently existed (p. 378).

We may, for the purposes of discussion here, consider the experimental results for what was perhaps, ultimately, the best of the trial-solutions, in which internal piers were tried in relation to different locations of the entrance; namely, solution M5 of Fig. 183 (b). This particular solution would involve the building of a pier 1350 feet long at the northern end of the Duncan Basin and the retention of the basin entrance at its present site. The periodograms obtained in the model experiments for this scheme (red), in comparison with the existing basin (yellow), are shown for the four corners of the dock in Fig. 215.

Trial-solution M5 would be a real solution if it reduced the magnitude of the internal oscillations to 25% of the maximum known to have occurred in the past. The criterion for judging the severity of Range occurrences in the past has been the record of the Lea tide-gauge in the Duncan Dock, situated not far from the E-berth corner, so that if solution M5 is to be regarded as satisfactory it must reduce the oscillations in the basin everywhere to below 25% of the 1.9 min. oscillation found in the model existing-basin at the E-berth corner. The 25% limit lines, thus defined, are shown in Fig. 215.

Three corners of the modified Duncan Basin comply with specified requirement for periods of oscillation less than 2.5 mins. (Fig. 215): the fourth corner gives a reduction to 50%. At periods above 2.5 mins., however, solution M5 increases the oscillations at the northern end of the basin to tremendous proportions and the periodograms for A and E-berths assume a very unfavourable appearance. The condition represented by the considerable peak at 3.6 mins. periodicity at the E-berth corner of the dock (Fig. 215) was characterised in the model by a violent flux of water round the 1350 ft. pier. This would almost certainly have its repercussions on shipping lying at G and H berths as well as alongside the new pier itself. The findings of the last chapter admittedly indicate that frequencies higher than this are the main culprits in producing critical ship motion, but they have also established that the longer periodicities are not completely without effect.

As a permanent solution of the Range problem scheme M5 is not very attractive, for it still leaves one corner of the dock in vulnerable condition. An important factor militating against its advocation is its susceptibility to oscillations of periodicities below, say, 1.5 minutes.

The sub-division of the northern end of the dock into two compartments by the pier is likely to create conditions favourable to the development of just those higher frequency oscillations which are most critical for ships. The model, unfortunately, was not very well suited to the examination of periodicities below about 1.2 minutes, but some idea of the possible outcome over this frequency band was secured by operating a plunger immediately outside the basin entrance. The comparative periodograms obtained by this means for the existing harbour and solution M3 (Fig. 183 (b)) are shown in Fig. 216 - it may be assumed that solution M5 will give a similar result to that of M3, which differed from it merely in having a shorter pier (950 feet).

The plunger method of testing is not wholly reliable, because some of the oscillations it enforces on the basin are not in existence in the external breakwater-shore oscillating system. Nevertheless, the indications of Fig. 216 are that the oscillations below 1.5 minutes in periodicity, so far from being reduced, are increased, as expected.

151. Solutions of Type 2C (Outer Basin Enclosures).

The general failure of trial-solutions of the 2B type might perhaps have been anticipated from the considerations of Section 145 (p. 430). The harbour, it would seem, requires more muzzling to diffuse the energy of the ground-swells. Simple reduction of the widths of the entrances will not be effective to any worthwhile degree (p. 431), so that the only remaining means of cutting down on the penetration of energy into the basins lies in the adoption of outer enclosures, within which the ground-swells can, at least, be partially dispersed.

Here it is as well to realise that the mere enveloping of the harbour in an outer basin enclosure will not necessarily see the end of the Range troubles. Unless the enclosure is well chosen or carefully designed as to position and shape in relation to the general topographical features of the harbour and the bay, it can become an echo-chamber for certain frequencies of waves, which by building up energy through resonance, may be capable of influencing the inner basins as much as ever. This would seem to be the principal reason for the failure of Mr. George Stewart's proposal for an outer basin (p. 379).

The oscillations within a basin of irregular shape are so complicated that it is generally impossible to predict in more than a very general way what its behaviour will be, especially if that behaviour is dependent also on the interaction of adjacent basins. It is here that model techniques, properly applied, are of such inestimable value.

In Section 129 (pp. 378-383), we described some of the experiments that led to the isolation of one form of outer basin that fulfilled all the requirements of a real solution to the Range troubles in the Duncan Basin. Particulars of this outer enclosure are given in Fig. 191. It cannot be claimed that this is necessarily the only arrangement that complies with the conditions: it was the only one the author succeeded in discovering up to the time of his transfer from Cape Town at the end of 1946. It is almost certain that other alternatives can be devised, but it may be difficult to make them conform to the requirements we laid down in Section 145 (p. 430). The particular in which they are likely to deviate most readily will be as regards their effect upon the general regime of oscillations outside the harbour.

The solution portrayed in Fig. 191 was based upon five principles (p. 380), which we believe to be both sound and desirable, and improvement, it seems, cannot be achieved by any other means without sacrificing at least one or more of those features.

It has been suggested that a solution of the type of Fig. 191, considered first and foremost as a scheme of expansion for the harbour, would be insufficient to meet the future needs of the port of Cape Town, and that the outer enclosure would have to be torn up ultimately to make room for something larger.

In the author's humble opinion it would be preferable at such a stage to consider extending the harbour on the northern side of the present breakwater, rather than to make further claims upon the spending beaches of the bay. Development to the north would entail laying down a new breakwater in fairly deep water and might create problems of accessibility from the landward side, but it might be worth the extra expense in the long run for the avoidance of troubles elsewhere. Only an adequate programme of model experimentation to investigate all the aspects involved could give a full and final answer on this point.

152. Solutions of Type 3A (Shock-Absorbing Protection at Entrances)

We turn to a consideration of what can be done to mitigate the hazard of the currents through the entrances of the basins (pp. 146, 429).

As these periodic currents cannot be eradicated by any physical means (cf. p. 432), they must be tolerated either by full reliance on the skill and knowledge of the pilots or by the use of devices to cater for the odd occasion when judgement may fail or the luck run out.

One obvious measure for protecting ships from the dangers of collision with fixed structures at the entrances would be the provision of shock-absorbing fenders or dolphins at the extremities or bull-noses of the entrances. The vertical suspended fender referred to on p. 438 would be ideal for this purpose.

153. Solutions of Type 3B (Warning Apparatus).

As an alternative to shock-absorbing fenders at the entrances, warning apparatus could be developed to ring a bell automatically in the Port Captain's Office, so that pilots, about to take ships in or out of the harbour basins, could be advised by radio-communication of the precise moment at which it would be safe to shepherd a large vessel in or out of a basin.

Probably the best device of this kind would be a continuously recording current meter of the electrical type referred to on pp. 77-78, placed on the sea-bed in the centre of a basin mouth. By means of relays the recording apparatus could be made to emit signals whenever the currents reached dangerous proportions.

Equally satisfactory as warning apparatus would be suitably placed tide-gauges of the Lea type, already in use at Cape Town. Here the gradient of rise and fall of water on the marigram would be an indication of the magnitude of the current in the entrance during long-period seiche action.

154. The Design of Harbours in Relation to Range-Action.

To conclude this work we may attempt to focus the light from such of the facets of this research as seem to be of importance to harbour designers.

(1). The harbours of the world that are most likely to experience troubles in the form of Range action will be those which lie on or near the tracks, in the line of approach, of the great atmospheric disturbances, such as the travelling depressions of the temperate zones and the cyclones of the equatorial regions, but more particularly those harbours which flank a wide expanse of ocean in these regions, where depth and openness favour the propagation of long swells.

(2). The bays and inlets along the coastlines in these areas will inevitably exhibit the phenomenon of seiches, the longer periodicities of which may even be dictated by the oscillations of the ocean within some hidden basin or canyon of the deep.

(3). If a bay conforms, in any sense, to a simple geometrical shape its natural periods of oscillation can probably be estimated with fair accuracy by mathematical means and some idea obtained as to the location of the nodes of the seiches.

(4). Bays which are fairly open will have a fundamental mode of oscillation in which the node will be found to lie at or near the mouth. Higher modes of oscillation will all have a node at the mouth in addition to other nodes whose distance apart will tend to lessen as the water shoals towards the head of the bay.

(5). Bays which are open to the sea through comparatively narrow entrance channels will probably exhibit, in addition to the modes of oscillation mentioned, other modes characteristic of fully enclosed basins of their particular shapes. The node of the fundamental seiche in a case of this kind will tend to lie near the middle of the lagoon.

(6). In the absence of a model study, the best means of locating a harbour within a bay which is subject to seiches, is by graphical determination of the expansion-fronts of incident and reflected waves. By following the procedure of Section 93, (p. 268), the approximate characteristics of the seiches can be determined.

(7). The graphical method will be found particularly valuable for orienting sea-defence works and for rapid estimation of the likely repercussions that might derive from any one scheme.

(8). In general, (other factors permitting), it will probably be found desirable, for the avoidance of serious Range-action, to locate the harbour near the mouth of an open bay or near the middle of a semi-enclosed bay. By so doing the harbour works will not seriously interfere with the natural regime of the bay and will lie in a zone where nodal lines are farthest apart. If the harbour is placed at the head of the bay where the nodal lines of the many possible seiches tend to be concentrated, not only will it be subject to the worst effects of the loop-ends of all the seiches, but it will tend to interfere with the natural order and will almost inevitably create a smaller echo-chamber within which some of the seiches of the bay will resonate.

(9). If a harbour near the head of the bay is unavoidable, great care should be exercised in the location of the breakwater lest the bight it creates should permit resonance of one of the seiches of the bay.

(10). It is desirable to ensure that the dimensions of the docks in the harbour are not such as to yield natural periods of oscillation which correspond with any of the external seiches. This may be difficult in a harbour near the head of a bay, owing to the numerous high-frequency seiches which may be engendered purely through the harbour creating a quasi-basin in that corner of the bay.

(11). As far as possible the length-breadth dimensions of harbour basins should be incommensurable. Dimensions which are integral multiples of each other are likely to favour the development of seiches.

(12). It is the higher frequency seiches of the order of, say, 2 minutes period and less that should receive particular attention. These are the oscillations that are likely to give trouble with shipping.

(13). Perhaps the most efficient means of stifling the effects of Range-action of the higher frequency type is by creation of a chain system of basins, the outer ones of which act as chokes for absorbing the energy of the ground-swells.

(14). Model studies of wave-action should preferably be conducted on models for which the distortion, or difference in the horizontal and vertical scales, is nil or of as small an order as possible.

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A list of works and technical literature consulted in the course of the research and the preparation of this thesis is appended below in the order in which annotations occur in the text. The sequence numbers relate to the corresponding numbers quoted at the end of footnotes. For convenience, the page in the text where any particular reference is first quoted is given in the right-hand column.

A considerable number of other references, consulted but not referred to in the text, has been omitted from this list as having no specific association.

The following abbreviations have been adopted in referring to technical journals, etc.:

Am. Geophys. Un.--American Geophysical Union
ASCE--American Society of Civil Engineers
ASME--American Society of Mechanical Engineers
Brit. Assoc. Adv. Sc.--British Association for the Advancement of Science
Calif. Inst. Tech.--California Institute of Technology
Civ. Engg.--Civil Engineering
Dict. Appd. Phys.--Dictionary of Applied Physics
Dk. & Harbr. Authy--Dock and Harbour Authority
Engg--Engineering
Engg News Rec.--Engineering News Record
Engr.--The Engineer
Expt. Statn.--Experiment Station
Inst. C. E.--The Institution of Civil Engineers (London)
Intern'l Nav. Congr.--International Navigation Congress
J--Journal
Mar. & Waterways Engg. Divn.--Maritime and Waterways Engineering Division
Mass. Inst. Tech.--Massachussetts Institute of Technology
Math.--Mathematical
Mech.--Mechanical
Ocean. Inst.--Oceanographic Institute
Phil. Mag.--Philosophical Magazine
Phil. Trans.--Philosophical Transactions
Phys.--Physical
Proc.--Proceedings
Q. J. Roy. Met. Soc.--Quarterly Journal of the Royal Meteorological Society
Rev. Gen.--Revue Generale
Rev. Sc. Instr.--Review of Scientific Instruments
Roy. Soc. Edinb.--Royal Society, Edinburgh
Roy. Soc. Lond.--Royal Society, London
S. A. Soc. C. E.--South African Society of Civil Engineers
Trans.--Transactions
Transl.--Translated
U. S. Nav. Inst.--United States Naval Institute

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NOTATION

The meanings of the symbols used in the mathematical expressions of the text are listed below for ready reference. Page numbers where symbols first appear are appended.

Small Letters

a	Cross-sectional area of circular cylinder or manometer limb	p. 342
b	Breadth or length of a wave front	236
c	Velocity of a wave in water(generally&on model scale)	107
d	Depth of water (generally & on model scale)	107
f	Fetch or Distance in which wind can generate waves	113
	Amplitude component of a periodic force	242
	Dimension of force (on model scale)	317
g	Acceleration due to gravity	107
h	Height or Vertical Projection of a ship's mooring rope	397
j	Algebraic Expression	239
k	Quantity dependent on configuration of a lake	238
	Algebraic Expression	245
	Constant of proportionality	392
l	Length or Horizontal Projection of a ship's mooring rope	397
m	Integer defining the nodality of a seiche in a closed basin	237
	Dimension of mass (on model scale)	317
	Number of berths in a harbour basin, occupied by ships	405
n	Integer, defining the nodality of a seiche	237
	Numerical Exponent depending on the characteristics of a ship's mooring ropes.	392
	Number of Rope Breakages per ship per day	404
p	Angular Frequency of a wave or seiche dependent on periodicity	107
q	Nodal Frequency of a wave or seiche dependent on wave-length	107
r	Ratio of maximum travel of a ship (from equilibrium position) in resonant oscillation to the travel just necessary to tighten the mooring ropes at bow or stern	394
s	Integer, defining the nodality of a seiche in an open basin	243
	Dimension of Distance (on model scale)	317
	Unstrained Length of ship's mooring rope	397
t	Dimension of Time (generally and on model scale)	107
u	Displacement of a moored ship from equilibrium position	392
x	Horizontal Distance in the direction of propagation of a wave	107
z	Vertical Distance above or below the free surface of water at rest	107

Capital Letters

A	Amplitude of Vertical Movement of a wave or oscillation	107
B	Width or Breadth of a basin	237
C	Ratio of the surface area of a basin to the cross-section area of its entrance or mouth	150
	Dimension of Velocity (in nature)	317
	Constant of proportionality	415
D	Diameter of a circular basin	239

Capital Letters (cont'd)

F - Dimension of Force (in nature) 317
G - Gradient or Constant of proportionality 401
H - Height of ship's fairlead or rope guide above mooring bollard on quay or wharf 398
J - Bessel Function 245
K - Algebraic Expression 245
L - Length of a basin 236
- Horizontal Distance between ship's fairlead or rope guide and mooring bollard on quay or wharf (for equilibrium position of the ship) 398
M - Dimension of Mass (in nature) 317
N - Total Number of mooring ropes holding a ship 392
P - Barometric Pressure 219
- Impact Pressure of ship against a quay or wharf 415
Q - Nodal Frequency of a wave or seiche, dependent on wave-length (in nature) 319
R - Ratio of Periodicities of the fundamental mode of oscillation in a lake to its second harmonic 239
S - Dimension of Distance (in nature) 317
T - Dimension of Time (in nature) 317
- Tension in ship's rope 392
U - Group Velocity of waves in water 111
- Ultimate Strength in Tension of ship's mooring rope 403
V - Current Velocity in flow of water 150
W - Displacement Tonnage of a ship in water 392
Y - Half the Beam or Width of a ship 415

Small Letters (Greek Alphabet)

α - Coefficient defining a product 326
- Factor defining susceptibility of berths in a harbour to Range-action 402
β - Coefficient defining the square of the breadth-length ratio for a basin 237
- Algebraic Expression giving the reciprocal of the average number of ship's ropes broken per berth during Range-action in a harbour basin 405
γ - Scale Ratio of Velocity of waves in a model to velocity of corresponding waves in nature 318
δ - Scale Ratio of Depth of water in a model to corresponding depth in nature 318
ϵ - Phase Angle or Epoch 233
ζ - Scale Ratio of Force in a model to corresponding force in nature 318
η - Vertical Displacement of a water particle from equilibrium position 108
θ - Factor of Correction or Ratio of times in nature to corresponding times on a model scale 326
λ - Wave-length of waves in water 107
μ - Scale Ratio of Mass in a model to corresponding mass in nature 318
ν - Number of mooring ropes holding a ship, broken during Range-action 403
ξ - Horizontal Displacement of a water particle from equilibrium position 108
π - Universal Coefficient (3.14159) 107
ρ - Density of fluid 342
σ - Scale Ratio of Distance in a model to corresponding distance in nature 318
τ - Periodicity of oscillation 107
- Scale Ratio of Time in a model to corresponding time in nature 318
ϕ - Coefficient of Distortion defining the ratio of vertical to horizontal linear scales for a model 326
ψ - Quantity depending on the configuration of a lake 238
ω - Angular Frequency of a beat oscillation 248

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