

CIV 5017Z: DISSERTATION FOR THE DEGREE OF MASTER OF ENGINEERING

# **Review of Current Asset Maintenance in South African Ports and Recommendations for Smart Port Maintenance**



**Prepared by:**

**Phumelele Mthembu**

**Supervised by:**

**Prof. Hans Beushausen**

Dissertation submitted in fulfilment of the requirements for the degree of  
Master of Engineering: Civil Infrastructure Management and Maintenance (CIMM)

Department of Civil Engineering, University of Cape Town, Private Bag Rondebosch, 7700  
South Africa 7700

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# Abstract

Transnet National Ports Authority's (TNPA's) waterside infrastructure is key to facilitating safe port navigation and operations in South Africa. Conflicting information regarding the asset condition of TNPA's infrastructure provides a need for objective asset condition assessments and ratings using international guidelines and standards. This qualitative research reviews the condition assessment guidelines prescribed in the TNPA Asset Maintenance Principles and Procedures (AMPP) Manual for waterside infrastructure. The research aims to understand the current challenges experienced with the asset condition assessments, evaluate the effectiveness of the condition assessment methods in assessing chloride-induced deterioration and evaluate how smart port maintenance can benefit TNPA. The Port of Cape Town's condition assessment data for waterside infrastructure, collected between 2020 and 2023, is used as a case study for this research.

The literature review discusses concrete structures in the marine environment in terms of their exposure conditions, durability, service life prediction and effective tests to assess chloride-induced deterioration. The benefits of smart port maintenance technology are explored using case studies from international ports such as the Hamburg Port Authority (HPA) in Germany and Norvic Port in Sweden. Insights are provided on how Digital Twin (DT) models can autonomously make maintenance decisions and improve maintenance strategies.

The methodology adhered to is informed by guidelines from the World Economic Forum's Strategic Infrastructure Report to assist governments and key stakeholders in developing comprehensive frameworks for the operation, maintenance and end-of-lifecycle decisions of existing infrastructure. Existing literature, TNPA data and case studies are used for the observations and recommendations. The main steps include conducting a status quo analysis of the current condition assessment methods and a benchmarking analysis which includes leveraging technology to improve maintenance in ports.

The four condition assessment methods used in TNPA to assess waterside infrastructure consist of the eyeball inspection, aerial survey, instrument measure and diving inspection methods. The observations found that the current asset condition ratings for TNPA's waterside infrastructure are based on incomplete condition assessment methods which do not effectively assess

chloride-induced deterioration. A recommendation is suggested to include cover assessments, delamination surveys and measurements of half-cell potential, corrosion rate and resistivity as part of the condition assessment methods with revised frequencies. Chloride profiling and service life prediction models are recommended to predict the remaining service life. A standardised asset condition guideline, which is aligned with the size of concrete defects, is also recommended for objective asset condition ratings.

To leverage technology, TNPA's current Systems, Applications, and Products in Data Processing (SAP) Plant Maintenance (PM) software is compared to smart technology used by international ports. The main limitation of the SAP PM software is its ability to only track and manage maintenance activities. DT technology is recommended due to its ability to diagnose the deterioration of port infrastructure and improve maintenance strategies. To implement DT technology in TNPA, the main enablers required include the installation of sensors which detect and diagnose deterioration and the use of Building Information Modelling (BIM) software. Limitations of implementing DT technology such as high costs, data security risks and the lack of standards and frameworks should be taken into account. Considering these implementation barriers, TNPA can currently ensure that inputs to the SAP PM software are informed by the recommendations provided in this research.

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# List of Acronyms and Abbreviations

|       |   |
|-------|---|
| AI    | Artificial intelligence   |
| AMPP  | Asset Maintenance Principles and Procedures   |
| AR    | Augmented Reality   |
| ASR   | Alkali-Silica Reaction  |
| BI    | Business Intelligence   |
| BIM   | Building Information Modelling  |
| BSD   | Ben Schoeman Dock   |
| CI    | Condition Indicator   |
| CMMS  | Computerized Maintenance Management System  |
| COVID | Corona Virus Disease  |
| CSIR  | Council for Scientific and Industrial Research  |
| DT    | Digital Twin  |
| ELISA | Energy Effective Logistics and Infrastructure Systems Assessment  |
| FAR   | Financial Asset Register  |
| FEM   | Finite Element Model  |
| fib   | International Federation for Structural Concrete  |
| GWIP  | Group Wiki Project  |
| HMI   | Human Machine Interface   |
| HPA   | Hamburg Port Authority  |
| iCRT  | Interactive Construction Tour   |
| IoT   | Internet of Things  |
| IRC   | Infrastructure Report Card  |
| LPR   | Linear Polarisation Resistance  |
| MOU   | Memorandum of Understanding   |
| MTEF  | Medium-Term Expenditure Framework   |
| OPEX  | Operational Expenditure   |
| NDT   | Non-Destructive Testing   |
| O&M   | Operation and Maintenance   |
| PTO   | Port Transportation and Operations  |
| RILEM | International Union of Laboratories and Experts in Construction Materials, Systems and Structures (in French) |

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|        |  |
|--------|--|
| RQ     | Research Question                                      |
| RUL    | Remaining Useful Life                                  |
| SAICE  | South African Institution of Civil Engineering         |
| SAMSA  | South African Maritime Safety Authority                |
| SAP    | Systems, Applications, and Products in Data Processing |
| SAP PM | SAP Plant Maintenance                                  |
| SHM    | Structural Health Monitoring                           |
| SOC    | State Owned Company                                    |
| TCC    | Transnet Corporate Centre                              |
| TNPA   | Transnet National Ports Authority                      |
| TPT    | Transnet Port Terminals                                |
| UPV    | Ultrasonic Pulse Velocity                              |
| VR     | Virtual Reality  |
| VTBM   | Virtual Tunnel Boring Machine                          |

# 1 Introduction

## 1.1 Background

### 1.1.1 Overview

Transnet National Ports Authority (TNPA) is responsible for the safe, effective and efficient economic functioning of the national port system in South Africa. It aims to achieve a World-Class Port status. One of the seven core functions of TNPA is to plan, improve, develop and maintain port infrastructure. TNPA's infrastructure is required to be world-class to allow successful imports and exports for South Africa.

TNPA owns nine commercial ports, namely Saldanha Bay, Cape Town, Mossel Bay, Port Elizabeth, Ngqura, East London, Durban and Richards Bay, with the ninth port being the small Port Nolloth. The nine ports have landside (buildings, retaining walls, roads, etc.) and waterside or marine (breakwaters, seawalls, quays and other berthing structures) infrastructure.

Out of the nine ports, the two ports with the most deteriorated infrastructure are Mossel Bay and Cape Town, judged by the average asset condition assessment ratings between 2017 and 2022 of 64% and 69% respectively. However, the Port of Cape Town has a more significant impact on TNPA operations, based on the revenue it provides. In the 2022/23 financial year, the Port of Cape Town provided a revenue of R1.9 billion, compared to the Port of Mossel Bay's R89 million. South Africa's fruit export industry is also largely dependent on the efficient functioning of the Port of Cape Town. Figure 1.1 provides an aerial view of the Port of Cape Town.

### 1.1.2 TNPA Asset Condition Assessments

TNPA uses the Asset Maintenance Principles and Procedures (AMPP) manual for infrastructure inspections. It provides guidelines for undertaking port maintenance to prevent the depreciation of the asset value. The AMPP manual covers civil, waterside, electrical and mechanical assets and buildings. The waterside assets include the waterside infrastructure, i.e. concrete structures in the marine environment, which enables safe port operations and navigation. The AMPP manual specifies condition assessment methods which entail the eyeball inspection, aerial survey, instrument measure and diving inspection methods. The Systems Applications and Products (SAP)

Plant Maintenance (PM) software is used by TNPA as its Computerised Maintenance Management System (CMMS) to manage asset maintenance. These condition assessment methods and tools are deemed sufficient to provide the condition of infrastructure in the Ports considering the deterioration mechanism that the assets are subjected to.



**Figure 1.1: Aerial view of the Port of Cape Town (Picture supplied by TNPA)**

### 1.1.3 Smart Port Maintenance

Port Authorities such as those in Hamburg, Germany, and Rotterdam, Netherlands, have leveraged technology to advance their maintenance. Sensors are used for monitoring the state of infrastructure assets in real time, which also enables the authorities to predict the possible remaining lifespan with more accuracy. The asset inspection process is automated with the incorporation of Artificial Intelligence (AI) by recognising deterioration and communicating the information. One of the most effective systems to achieve this is by using a Digital Twin (DT). This is a computer-generated simulation of a physical entity or system throughout its lifecycle. Digital tools, sensors and real-time data are used to create, test, build and monitor the

infrastructure. DTs require continuous calibration throughout their lifecycle to ensure that they adhere to a constant model of reality.

## 1.2 Problem Statement

### 1.2.1 TNPA's AMPP Asset Condition Methods

The asset condition assessment methods stipulated in the current TNPA AMPP Manual for waterside infrastructure include the following:

- The eyeball inspection method, which entails the visual assessment of a concrete structure;
- The aerial survey method, which is conducted by the Council for Scientific and Industrial Research (CSIR), entails the use of aerial photography to assess the damage to the armour of concrete structures;
- The diving inspection method, which consists of assessing and measuring the deterioration of inaccessible/submerged parts of a structure;
- The instrument measure method, which entails measuring the deterioration of a concrete structure using equipment and instruments.

The challenge that the Ports have experienced with the eyeball inspection method is that it is dependent on the experience of the inspector. In addition, the standardised inspection sheets and reports used during inspections do not contain set rating systems to classify the severity of the deterioration, making them further rely on the eyeball method and the inspector's experience. An extract of a typical asset condition rating inspection sheet is provided in Annexure A. It shows that the overall condition assessment ratings are weighted and purely reliant on the ratings provided by the assessor. Therefore, the condition assessment of waterside infrastructure is neither reliable nor aligned with international condition assessment manuals and guidelines.

### 1.2.2 TNPA's Asset Management Software

The Systems, Applications, and Products in Data Processing (SAP) Plant Maintenance (PM) software is the Computerised Maintenance Management System (CMMS) used by TNPA to centralise maintenance information and facilitate the processes of maintenance operations. It is mainly used for the development of the approved maintenance schedule and the monitoring of the progress of inspection activities. However, the actual asset condition assessment is still dependent

on the current TNPA AMPP Manual's methods mentioned above. The effectiveness of this software in enabling the ports to perform smart port maintenance requires evaluation.

### **1.3 Aim of the Research**

The research aims to determine the shortcomings of the current TNPA condition assessment approach for waterside infrastructure. In addition, it aims to develop insights gained from international best practices to assist with improving TNPA's asset condition assessment methods. It also aims to recommend smart port maintenance strategies to optimise the current maintenance software used.

### **1.4 Objectives**

The following objectives will be addressed in the research:

- Perform a literature review on factors affecting the service life of port infrastructure and discuss associated maintenance strategies.
- Provide a summary regarding the current problems experienced with the waterside infrastructure operated by TNPA.
- Review the use of DT technology for smart port maintenance by international ports.
- Recommend a standardised classification system to categorise defects for visual condition assessments for the revised TNPA AMPP Manual.
- Recommend effective testing methods that can be used to assess the deterioration of concrete structures in marine environments.
- Evaluate how DT technology can be applied in TNPA to improve the management of port infrastructure.

### **1.5 Scope and Limitations**

The following scope and limitations apply to this research:

- This research is limited to evaluating the condition assessment of TNPA's waterside infrastructure. The main waterside infrastructure that will be analysed is limited to concrete structures in the marine environment, i.e. breakwaters, dry docks, quays and seawalls.

- The Port of Cape Town’s data is used as a case study based on the port’s low asset condition ratings between 2017 and 2022, and considering its contribution to TNPA’s asset base and revenue.
- The research is limited to assessing concrete deterioration and rating the condition of concrete structures. It does not include the associated repair and rehabilitation measures.
- The smart port technology that is evaluated is based on the maintenance and health monitoring phase of port infrastructure and not the entire lifecycle of a concrete structure.

## 1.6 Research Questions

The following Research Questions (RQ) will be investigated in this research:

- RQ1: What challenges is TNPA experiencing pertaining to the maintenance of its waterside infrastructure?
- RQ2: How does TNPA’s asset condition assessment compare to international best practices and standards for asset condition assessments in the marine environment?
- RQ3: How can smart technology be used to improve port maintenance in TNPA?

## 1.7 Methodology

The methodology approach conducted for this dissertation, which is expanded on in Chapter 3, is qualitative research using existing documentation, literature and case studies to meet the research objectives. The procedures, discussed in Chapter 3, are recommended by the Strategic Infrastructure Report, which was developed by the World Economic Forum. It is based on 200 real-life examples and case studies and aims to assist with maximising asset utilisation, reducing the operation and maintenance (O&M) costs and increasing the infrastructure’s value over its lifetime.

## 1.8 Structure of the Report

The report is structured as follows:

- Chapter 1 provides the introduction and scope of the research which includes the problem statement, aim, and research questions.

- Chapter 2 provides a literature review related to waterside infrastructure and smart port maintenance.
- Chapter 3 provides the methodology adhered to for this qualitative research.
- Chapter 4 provides a review of the TNPA condition assessment guidelines using the Port of Cape Town as a case study. It also includes recommendations for best practices based on the literature review in Chapter 2.
- Chapter 5 provides a review of the maintenance technology used in TNPA. Recommendations for best practices accompanied by a gap analysis are also provided based on the literature review in Chapter 2.
- Chapter 6 provides the conclusions and recommendations of the research.
- Chapter 7 provides the full list of references used and Chapter 8 contains the annexures extracted from the national TNPA and Port of Cape Town's condition assessment data.

## 2 Literature and Industry Review

This section aims to provide a detailed literature review to provide an understanding of TNPA's waterside infrastructure and condition assessments as well as the factors affecting the service life and maintenance of concrete structures in the marine environment. Case studies are also discussed to provide insights into asset maintenance best practices from international ports.

### 2.1 Overview of TNPA's Waterside Infrastructure

The waterside infrastructure in TNPA enables safe and efficient port operations. The following waterside infrastructure plays a key role in the port system (Transnet National Ports Authority, 2016):

- **Breakwaters** protect the inner channels of the port's entrance by providing safe and calm water for the navigation of vessels. The closure of entrance channels due to breakwater failure would have a high impact since the entrance channels in most of the ports offer single-lane traffic. Most breakwaters are comprised of interlocking concrete blocks called dolos. Figure 2.1 shows a section of the Main Breakwater at the Port of Cape Town.
- **Quays** are grouped with other berthing structures including jetties, dolphins and berths. They support the transfer of cargo between vessels and landside facilities. This includes the berthing of vessels and loading/unloading equipment. Quay walls generally consist of caisson walls, block walls, steel sheet-pile walls, deck-on-pile walls and counter-fort walls. Jetties are generally deck-on-pile structures constructed perpendicular to the land. Dolphins generally consist of caissons, block-work, and concrete decks on piles. Figure 2.2 shows a sheet pile wall at the Port of Port Elizabeth and Figure 2.3 shows the C-Series Berths at the Port of Ngqura.
- **Dry docks** are ship repair facilities to accommodate the hull (body) inspection or condition survey that ships must perform every four years, as per South African Maritime Safety Authority's (SAMSA's) legal requirements. Failure to perform these required inspections allows SAMSA to stop the ship from sailing. Dry-dock facilities include a workshop as well. The Port of East London's dry dock facility is shown in Figure 2.4.

- **Seawalls, or revetments**, are constructed for slope or embankment protection against water or wave action. The common type in ports is the closed-type seawall, which is stone-pitched and overlain with concrete plaster. Due to the problems experienced with over-dredging around the toe area and the leaching of fines through the seawall, ports are considering designing open-type seawalls, which consist of filter fabric overlain with hand-stone on the slope. The Port of Cape Town’s A-Berth seawall, which is stone-pitched and overlain with concrete blocks (dolos), is shown in Figure 2.5.



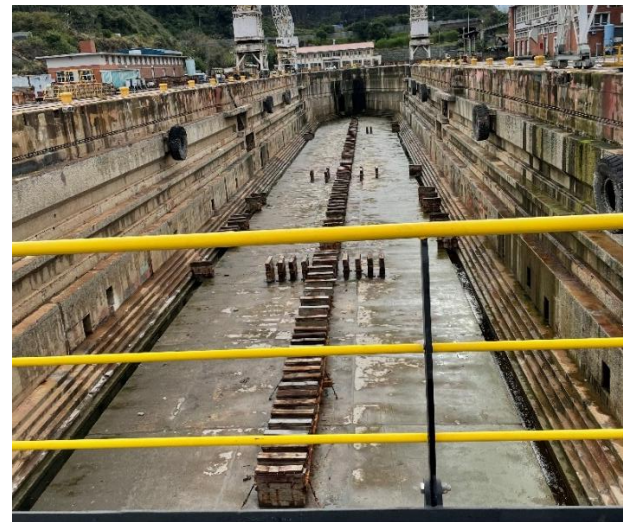
**Figure 2.1: Table Bay breakwater at the Port of Cape Town (Picture supplied by TNPA)**



**Figure 2.2: Sheet pile wall at the Port of Port Elizabeth (Picture supplied by TNPA)**



**Figure 2.3: C-series berths at the Port of Ngqura (Picture supplied by TNPA)**



**Figure 2.4: Port of East London’s Dry Dock Facility (Picture supplied by TNPA)**



**Figure 2.5: Port of Cape Town's A-Berth seawall (Picture supplied by TNPA)**

## **2.2 TNPA's Current Asset Condition Assessment Methods**

### **2.2.1 Port Condition Assessment Methods**

This section describes the current asset condition assessment methods as described in the TNPA AMPP Manual for each waterside infrastructure (Transnet National Ports Authority, 2016).

#### **2.2.1.1 Breakwaters**

The following methods are prescribed:

- The eyeball inspection method should be performed at least once a year and preferably during low spring tides. The main items that should be inspected are any defects/deterioration of the breakwater concrete units and any displacement/settlement of armour, which could be an indication of possible toe failure.
- The aerial survey method, conducted by the Council for Scientific and Industrial Research (CSIR), assesses breakwater units through a Memorandum of Understanding (MOU) between CSIR and Transnet SOC Ltd. This breakwater monitoring consists of analysing aerial photographs every year captured at pre-set coordinates. The main defects detected are changes in the breakwater armour or the movement of breakwater units.

#### **2.2.1.2 Dry-Docks**

The following methods are prescribed:

- The eyeball inspection method should be performed at least once a year and should inspect items such as signs of cracks, severe spalling, settlements, handrails, tunnels, ladders and conduits amongst others.
- The instrument measure is performed after the eyeball inspection, as and when required, for further evaluation. The determination of the concrete cover of reinforcing steel in structures, salt ingress, settlements, and fire or accident damage can be conducted using this method.

### **2.2.1.3 Quays and other berthing structures**

The following methods are prescribed:

- The eyeball inspection method should be performed at least once a year, or at shorter intervals as required, and preferably during low spring tides. Items/defects such as the cope-line levels, signs of cracks, severe spalling, drainage, surfacing, tunnels, bollards, fenders and ladders should be assessed during the inspection.
- The diving inspection should be performed at least once a year or at shorter intervals as required. Items/defects such as the prop-wash, toe integrity, scour protection, structure's condition below the water level and unwanted material such as containers, cables and tyres should be assessed during the inspection.
- The instrument measure is performed after the eyeball inspection, as and when required, for further evaluation. The determination of the concrete cover of reinforcing steel in structures, salt ingress, settlements, accident damage, seabed levels and unwanted material, e.g. tyres and cables, can be conducted using this method. In addition, a sonar survey is also recommended for underwater assessments.

### **2.2.1.4 Seawalls**

The following methods are prescribed:

- The eyeball inspection method should be performed at least once a year, preferably during low spring tides, as well as after a severe storm. The main items to be assessed are any visible damages to the seawall including damaged/missing protective layers and displacements/settlements of the embankment, which could indicate possible toe failure.

- The diving inspection should be performed at least once a year and should assess the prop-wash, toe integrity, scour protection and structure’s condition below the water level.
- The instrument measure method can be performed after the eyeball method for further evaluation. This consists of the measurement of settlements using survey equipment and the measurement of seabed levels through a sonar survey. The sonar survey also confirms the existence of prop-wash.

## 2.2.2 TNPA Asset Condition Ratings

The TNPA AMPP Manual specifies the items that should be given a rating for each waterside infrastructure. In addition, a weighting is allocated for the computation of the final overall asset condition rating. The rating for each item is provided by the assessor during the inspection based on their view of the asset’s deterioration. All asset condition ratings are accompanied by the asset condition inspection report. Table 2.1 shows the breakdown of how each waterside infrastructure should be weighted for the asset condition rating. Table 2.2 provides the TNPA AMPP Manual’s interpretation of an asset’s status based on the condition rating provided. Annexure A shows an extract of the Port of Cape Town’s Asset Condition Rating spreadsheet that was compiled for the 2022 condition assessment. A percentage input is provided by the port’s engineer for the “Actual Assessed Condition Rating” as guided by the rating status provided in Table 2.2. Thereafter, the spreadsheet calculates the “Weighted Actual Condition Rating” based on each asset’s weighted breakdown in Table 2.1.

**Table 2.1: Weighted breakdown of the asset condition rating for waterside infrastructure (Transnet National Ports Authority, 2016)**

| Breakwaters   | Seawalls   | Quays  | Dry Docks   |
|---|--|--|---|
| <ul style="list-style-type: none"> <li>• Armour outer (55%)</li> <li>• Armour inner (10%)</li> <li>• Toe - outer (8%)</li> <li>• Toe - inner (5%)</li> <li>• Splash wall (10%)</li> <li>• Top structure (10%)</li> <li>• Services (2%)</li> </ul> | <ul style="list-style-type: none"> <li>• Armour (50%)</li> <li>• Toe (25%)</li> <li>• Backup area (15%)</li> <li>• Services (10%)</li> </ul> | <ul style="list-style-type: none"> <li>• Wall / piles (30%)</li> <li>• Cope / deck (20%)</li> <li>• Toe (15%)</li> <li>• Bollards (8%)</li> <li>• Fenders &amp; chains (10%)</li> <li>• Ladders (2%)</li> <li>• Service Tunnel (10%)</li> <li>• Services (5%)</li> </ul> | <ul style="list-style-type: none"> <li>• Walls (15%)</li> <li>• Gates (15%)</li> <li>• Steps, landings, ledges (10%)</li> <li>• Tunnels, conduits (10%)</li> <li>• Fenders (10%)</li> <li>• Crane-rails (10%)</li> <li>• Hydrants (5%)</li> <li>• Markings (5%)</li> <li>• Hatches, manholes, crane-boxes (5%)</li> <li>• Handrails, escape-ladders (10%)</li> <li>• Flood and emergency valves (5%)</li> </ul> |

**Table 2.2: Asset Condition Rating status for all TNPA infrastructure (Transnet National Ports Authority, 2016)**

| Rating (%) | 1-10   | 11-20               | 21-30     | 31-40 | 41-50        | 51-60 | 61-70        | 71-80 | 81-90           | 91-100  |
|------------|--------|---------------------|-----------|-------|--------------|-------|--------------|-------|-----------------|---------|
| Status     | Unsafe | Very Poor to Unsafe | Very Poor | Poor  | Fair to Poor | Fair  | Good to Fair | Good  | Perfect to Good | Perfect |

## 2.3 National Assessment of TNPA Ports

The South African Institution of Civil Engineering (SAICE) is a voluntary association of civil engineering professionals. As a public service, the institution prepares the assessment of the condition of public infrastructure in its Infrastructure Report Card (IRC). The state infrastructure in each sector and the reasons for its changing condition are provided in the report. Infrastructure is graded on a scale ranging from A to E. This grading provides insights into the current condition of the infrastructure and how policy and management decisions have affected it (South African Institution of Civil Engineering, 2022). Table 2.3 below provides a summary of the description of the IRC grading definitions.

**Table 2.3: Summary of the SAICE IRC grading definitions (South African Institution of Civil Engineering, 2022)**

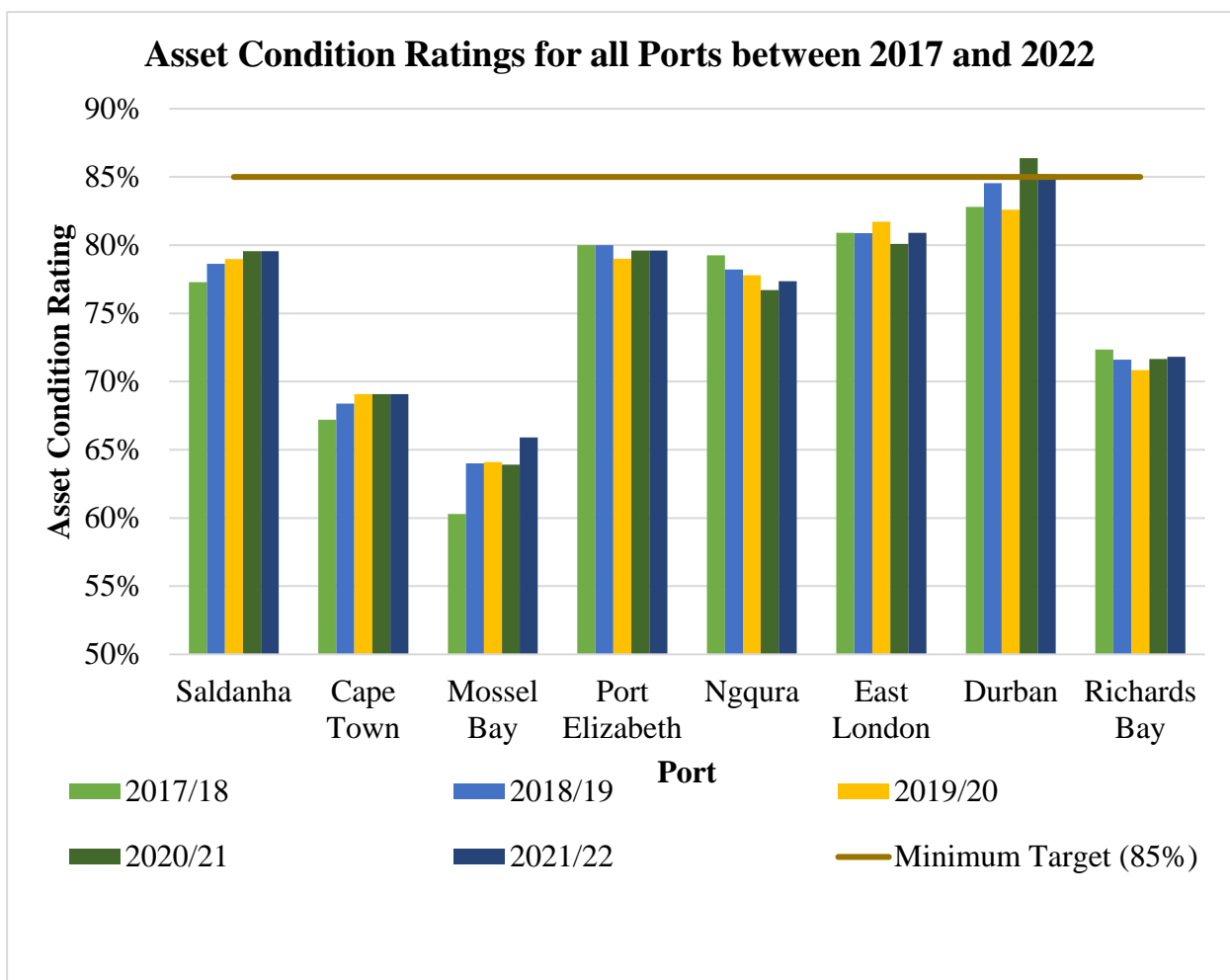
| SAICE IRC Rating                       | Description   |
|--|---|
| <b>A:<br/>World- Class</b>             | Infrastructure is comparable to the best internationally in every respect. It is in excellent condition and well-maintained, with the capacity to endure pressure from unusual events.          |
| <b>B:<br/>Fit for the future</b>       | Infrastructure is in good condition and properly maintained. It satisfies current demands and is sufficiently robust to deal with minor incidents.  |
| <b>C:<br/>Satisfactory for<br/>Now</b> | Infrastructure condition is acceptable although stressed at peak periods. It will need investment in the current Medium-Term Expenditure Framework (MTEF) period to avoid serious deficiencies. |
| <b>D:<br/>At Risk of Failure</b>       | Infrastructure is not coping with normal demand and is poorly maintained. It is likely that the public will be subjected to severe inconvenience and even danger without prompt action.         |
| <b>E:<br/>Unfit for Purpose</b>        | Infrastructure has failed or is on the verge of failure, exposing the public to health and safety hazards. Immediate action is required.  |

The 2017 IRC emphasised the need for refurbishing the TNPA breakwaters. In a 2018/2019 assessment conducted by the Council for Scientific and Industrial Research (CSIR), all the TNPA breakwaters were deemed to be in good condition. The Port of Cape Town, however, was highlighted to be the main outlier where sections of the breakwater required urgent repair. The dry dock facilities have been neglected by TNPA in terms of staffing and maintenance. An attempt to remedy the drydocks was introduced through the government-driven Operation Phakisa projects

which were earmarked to be completed in 2019. However, to date, most of the projects have not yet been successfully completed and the condition of the dry docks is still a concern for TNPA.

The TNPA commercial ports achieved an overall IRC Grade of B minus in the 2022 SAICE IRC. This implies that the ports have well-maintained infrastructure that satisfies their current demands. The standards and regulations in TNPA that govern infrastructure condition assessments and the maintenance, repair and rehabilitation regimen in the Ports enabled TNPA to obtain this rating. However, the condition of the dry docks used for ship repair has been relatively neglected due to a reduction in staff (South African Institution of Civil Engineering, 2022).

Parallel to the SAICE IRC grading provided above, TNPA annually rates its port infrastructure using the asset condition rating system discussed in Section 2.2 above. Figure 2.6 shows a graphical view of the asset condition ratings between 2017 and 2022 for all ports. The full asset condition ratings for each port have been obtained from TNPA and are provided in Annexure B. The overall average of the asset condition ratings ranges between 75.0% (in 2017/18) and 76.2% (in 2021/22). These ratings are below the minimum target asset condition rating of 85%, as per the TNPA AMPP Manual. In general, the minimum rating has rarely been achieved by most ports, with the Port of Durban achieving the highest rating with an asset base of R 21.8 billion, which is 27.5% of the total TNPA asset base. The Ports of Mossel Bay and Cape Town are the worst-performing ports, which have an asset base of R 1.2 billion and R 15.8 billion respectively. These consist of 1% and 16.3% of TNPA's total asset base respectively. Of the two underperforming ports, the state of Cape Town's assets is of great concern as shown by both the SAICE IRC and TNPA ratings.



**Figure 2.6: Ports’ Asset Condition Assessment Ratings between 2017 and 2022 (Data supplied by TNPA)**

While the SAICE IRC offers an aggregated rating intended to assess the condition of SA port infrastructure, its reliability is a matter of concern. This is attributed to the information sources and the inherent rating system, both of which are supplied by TNPA. In addition, a comparison of this rating to the TNPA AMPP Manula’s asset condition rating is not aligned since the minimum rating of 85% has only been achieved by one port since 2017. Therefore, to gain a more dependable assessment of the state of South African port infrastructure, there is a need for an objective rating system that is independent.

## 2.4 Concrete Structures in the Marine Environment

### 2.4.1 Deterioration Mechanism

The main challenge affecting the durability of concrete structures in the marine environment is reinforcement corrosion due to the presence of chlorides, air and water. A passive oxide layer forms around reinforcing bars in concrete due to the formation of hydroxide ions as a result of the cement hydration process. This layer protects the steel from corrosion. However, the ingress of chloride ions in the presence of oxygen and moisture neutralises the layer and reduces its pH value. This forms rust which gradually expands and creates one or more of the following flaws, which reduce the service life and load-bearing capacity of concrete structures:

- Longitudinal cracks at the concrete cover,
- Reduction of steel cross-section, and
- Reduction of the bond between concrete and steel.

In addition, factors such as inadequate concrete cover depth, the presence of cracks as well as poorly compacted and porous concrete increase the risk of reinforcement corrosion in this environment (James, et al., 2019).

The influence of cracks on the deterioration of concrete structures has been proven to be detrimental. The presence of cracks accelerates chloride-induced corrosion and impairs the durability of concrete structures due to the increase in the penetration paths which enable the initiation and propagation of reinforced steel corrosion. Research by Otieno, et al. (2016) investigated, amongst others, the impact of crack width on the corrosion rate of concrete specimens which were exposed to the marine environment in the tidal zone. The beams were pre-cracked using a flexural loading machine. The batch was separated into laboratory- and field-exposed environments over a period of 122 weeks (or 2.25 years). A comparison of the corrosion rate ( $i_{corr}$ ) was done for concrete specimens with the same environment, cover depth and concrete quality (i.e. binder type and w/b ratio) but with different crack widths ( $w_{cr}$ ). The results showed that the corrosion rate increased with an increase in crack width. Table 2.4 shows the results of the increase in the corrosion rate with increasing crack widths for different concrete mixes.

**Table 2.4: Effects of crack widths ( $w_{cr}$ ) on the corrosion rate ( $i_{corr}$ ) (Otieno, et al., 2016)**

| Mix label | Cover (mm) | Percentage change in corrosion rate due to increase in $w_{cr}$ (%) |       |                       |       |                 |       |
|-----------|------------|---|-------|-----------------------|-------|-----------------|-------|
|           |            | Uncrack. → Incip. crack   |       | Incip. crack → 0.4 mm |       | 0.4 mm → 0.7 mm |       |
|           |            | Lab   | Field | Lab                   | Field | Lab             | Field |
| PC-40     | 20         | +50   | +47   | **b                   | +9    | +38             | +28   |
|           | 40         | -*  | -     | -                     | -     | +30             | +15   |
| SL-40     | 20         | +15   | +8    | +25                   | **c   | +51             | +30   |
|           | 40         | -   | -     | -                     | -     | +15             | +23   |
| SL-55     | 20         | +14   | +25   | +20                   | +6    | +56             | +26   |
|           | 40         | -   | -     | -                     | -     | +27             | +15   |
| FA-40     | 20         | +21   | +20   | +31                   | +2    | +27             | +13   |
|           | 40         | -   | -     | -                     | -     | +22             | +31   |
| FA-55     | 20         | **a   | +11   | +51                   | +13   | +33             | +21   |
|           | 40         | -   | -     | -                     | -     | +25             | +23   |

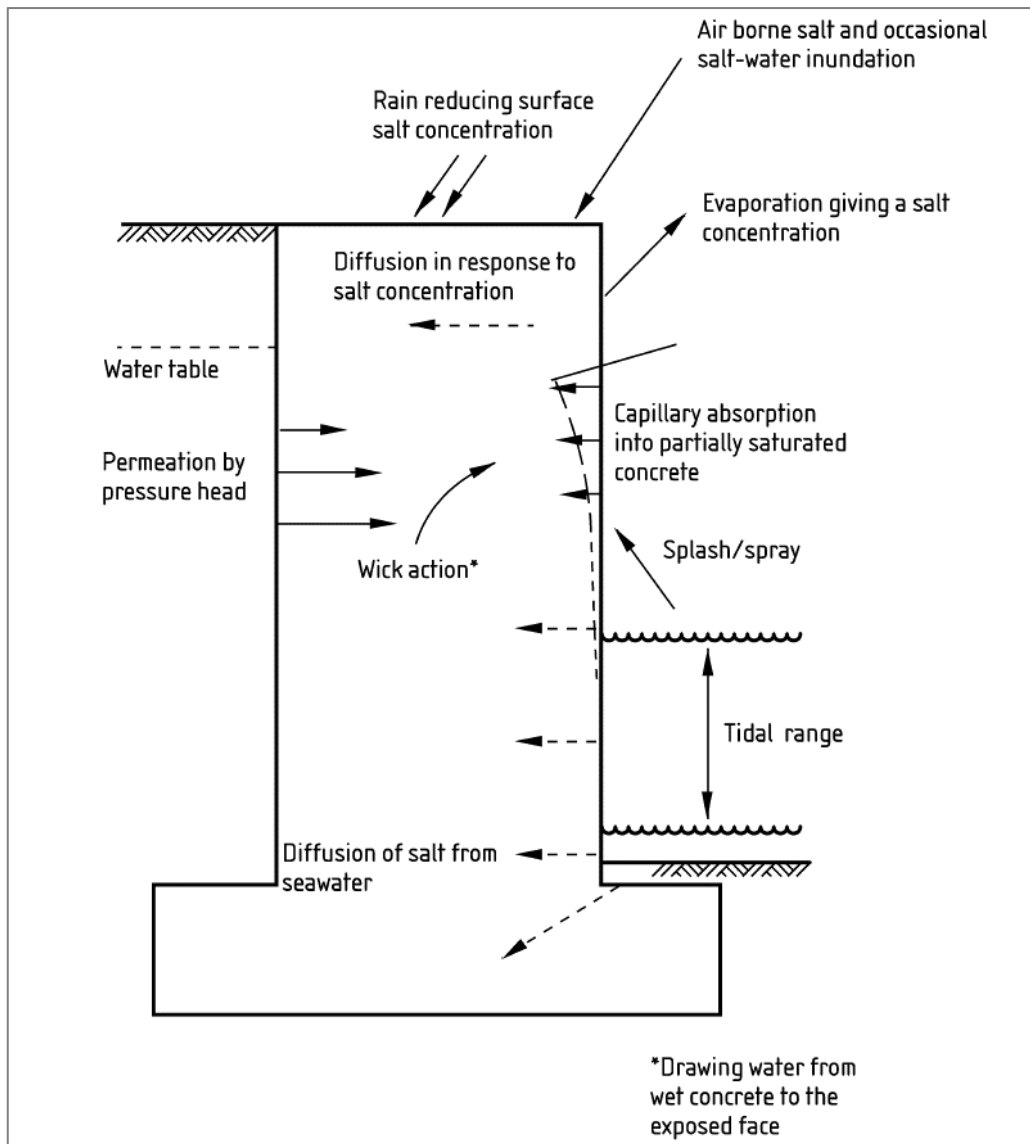
\* Note: Incipient-cracked specimens only made for 20 mm cover.

\*\* % change in  $i_{corr}$  not included because a reduction in  $i_{corr}$  due to increase in  $w_{cr}$  was obtained.

a: -13%, b: -18%, c: -1%

## 2.4.2 Marine Exposure Environments

Concrete structures in the marine environment can be classified into different zones according to their exposure conditions. The fib model code (International Federation for Structural Concrete, 2010) classifies three zones, namely Classes XS1, XS2 and XS3. Class XS1 categorises structures exposed to airborne salt but not in direct contact with seawater. According to SANS 10100, this includes structures that are within 30 km of the sea. This is based on the ability to facilitate chloride ingress and reinforcement corrosion based on onshore winds and ambient Relative Humidity (RH). Class XS2 categorises permanently submerged structures. Diffusion is the main transport mechanism for chloride ions. The lack of oxygen in this zone limits the reinforcement corrosion. Class XS3 categorises structures in the tidal, splash and spray zones. These structures in the tidal zone experience cyclical wetting and drying periods, therefore, the main transportation mechanisms for chloride ions are a combination of absorption, diffusion and convection. This leads to a higher concentration of chloride ions in the convection zone of the concrete structure. The chloride ingress experienced by structures in the tidal zone is higher than those in submerged zones and as high as those in the splash zones. In a conservative approach, the tidal zone should be considered the most severe exposure class (Beushausen, et al., 2021). Figure 2.7 shows the different exposure condition zones for a marine concrete structure.



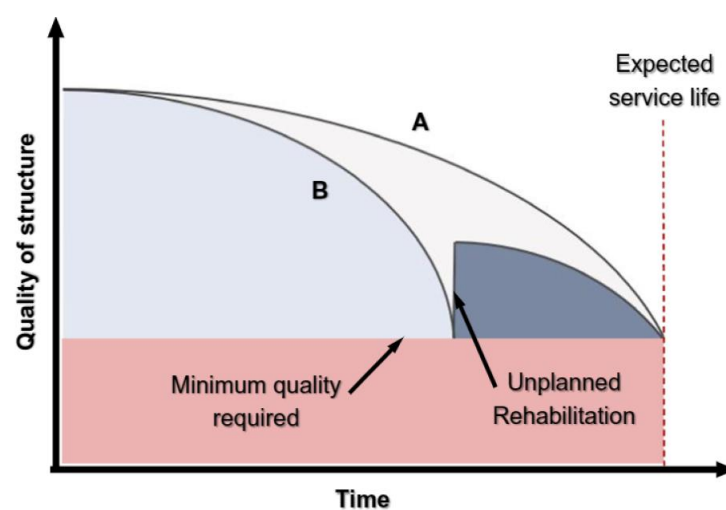
**Figure 2.7: Exposure condition zones for concrete in marine environments (British Standards Institution, 2000)**

A case study by Costa & Appleton (2002) investigated the deterioration of reinforced concrete structures in the marine environment in Portugal which are subjected to different wet and dry cycle periods. Two severely deteriorated docks located in an area with mild temperatures were investigated. Delamination and spalling of the concrete cover were the main defects observed for the docks after 10 years of service. The concrete covers ranged between 20 and 60 cm. Chlorides were found to be the main aggressive elements over a testing period of one year and the carbonation depths were much lower than the concrete cover. The walls obtained low resistivity values of 4 to 8 k $\Omega$ -cm, which corresponds with high corrosion rates. The case study also found that the internal walls showed higher levels of deterioration than the bottom and external walls. The upper part of the internal walls experienced cyclical wet and longer drying periods, making

the dominant transport mechanism absorption. The higher levels of chloride concentration, low resistivity and the easily accessible oxygen due to the long drying periods all contributed to the early spalling of the concrete cover. The lower part of the internal walls experienced frequent wet and dry cycles, which meant the concrete was more saturated than the higher walls. Therefore, the dominant transport mechanism in the lower walls was diffusion. The corrosion in this region had limited oxygen, which explains the less severe spalling witnessed in this area of the wall. In conclusion, the duration of the wet and dry cycles had an effect on the type of cracking and spalling experienced by concrete infrastructure in the marine environment.

### 2.4.3 Durability and Service Life Estimation

Infrastructure management and maintenance play a role in predicting the durability performance of concrete structures. The infrastructure owner is responsible for defining an asset's required service life taking into account other stakeholders and the society. Service life prediction is defined as the ability to predict the time period over which a structure can fulfil its intended function without reaching its serviceability or durability limit states (Alexander & Beushausen, 2019). The impact of the durability of a structure over time is shown in Figure 2.8 below. The graph represents the trajectory of the deterioration of two structures over a period of time. Structure A has sufficient durability, making it able to withstand deterioration prior to reaching unacceptable quality standards to reach its expected service life. Structure B, on the other hand, deteriorates at a faster rate due to its insufficient durability. It will require unplanned rehabilitation during its service life to maintain acceptable quality standards and reach its expected service life. The deterioration and required rehabilitation of a structure should be managed by the owner of the infrastructure.



**Figure 2.8: Schematic illustration of a structure's deterioration over its service life (Alexander & Beushausen, 2019)**

Durability design and specification approaches can be categorised as either prescriptive or performance-based. While the prescriptive approach determines limiting values for concrete mix compositions and materials, the latter is preferred due to its focus on transport-related properties to measure relevant concrete properties. Moreover, and most importantly, it integrates durability requirements and designs through service life models, which enables the estimation of the service life of a reinforced concrete structure. Research by Alexander & Thomas (2015) emphasises the advantages of performance-based approaches to predict durability and develop service life modelling. The as-built quality of a structure can be determined through performance testing where more information can be provided regarding the expected performance of the existing concrete structure. This can be achieved by using appropriate durability indicators which represent the deterioration of a structure during its service life. For reinforced concrete structures in the marine environment, the durability indicators include water absorption, sorptivity, porosity, diffusivity, conductivity, resistivity and electrical migration. These parameters are then used as inputs for service life models which can estimate the remaining service life of a structure.

## **2.5 Testing for Deterioration in the Marine Environment**

To preserve concrete structures and enable them to perform their functions over their service life periods, structures must be tested for deterioration and rehabilitated effectively. A review by James, et al. (2019) discusses the various tests to assess the deterioration of concrete structures in coastal environments as well as the appropriate repair methods. It provides the following guidelines to determine the extent of deterioration:

- Determine the cause of corrosion by assessing the results of concrete quality tests, compressive strength tests, cover depth measurements and elasticity modulus tests. These tests can provide more information on the quality of the concrete.
- Determine the areas of deterioration by performing Non-Destructive Tests (NDTs) and, where possible, extract samples for durability testing.
- Investigate cracks due to their ability to accelerate corrosion.
- Predict the remaining service life by analysing durability test results.

### **2.5.1 In-situ Testing**

The following two surveys can be performed to determine the location of deteriorated concrete surfaces (Beushausen & Louw, 2021):

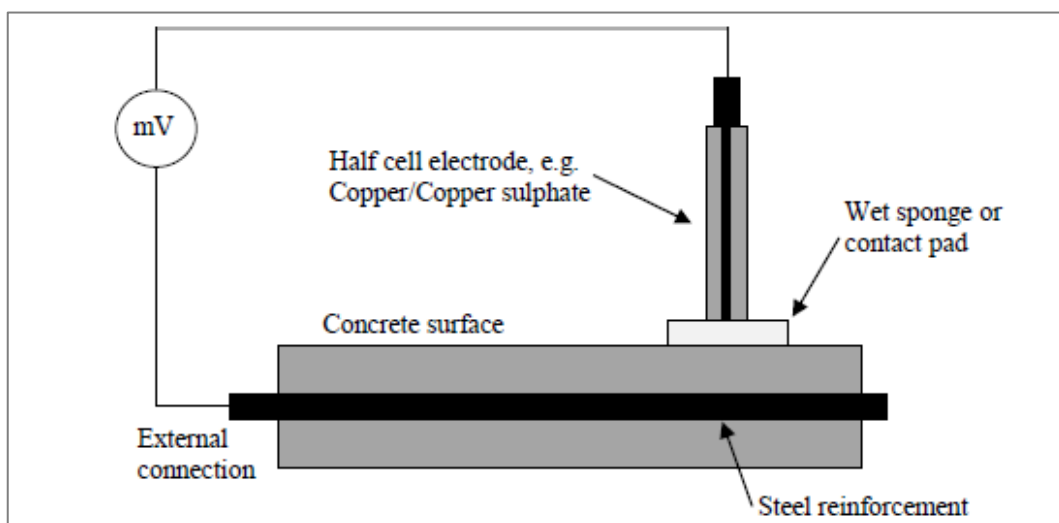
- **Cover assessments** are conducted using a cover meter to locate the position and depth of reinforcing steel in a structure. The measured cover can be compared with the design cover for marine concrete structures. According to Mackechnie & Alexander (1997), the recommended range of cover depths for marine structures should be between 50 and 75mm. However, cover measurements are unreliable for reinforcing steel that is closely spaced, located at deep depths (i.e. more than 80mm) or in the presence of a magnetic material. Figure 2.9 shows a cover assessment being conducted on site.
- **Delamination surveys** are conducted with a hammer by marking up areas with a hollow sound to identify problem areas on a concrete surface. These areas can be caused by reinforcement corrosion. The survey may underestimate the full extent of the damage in these areas. Therefore, it should not be considered a definitive method to identify the damage to a concrete structure. To supplement the delamination survey results, radar and ultrasonic instruments may provide further information at greater depths.



**Figure 2.9: Cover depth assessment on site (Beushausen & Louw, 2021)**

Alexander, et al. (2012) discuss three main measurements that can be used to assess the probability, severity and extent of reinforcement corrosion in concrete structures. These can be conducted on problem areas that have been identified on a concrete structure. They can be summarised as follows:

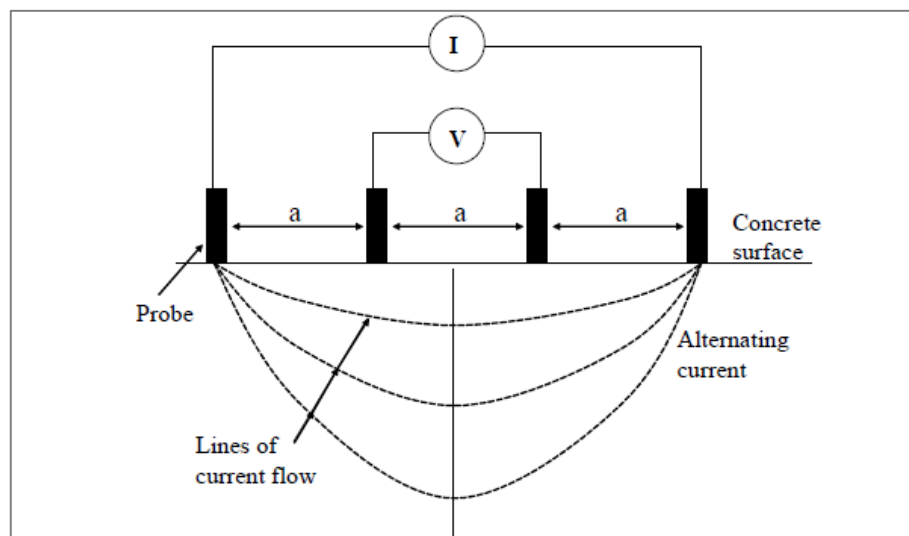
- **Half-cell potential measurements** are qualitative measurements that enable one to determine the probability of reinforcement corrosion activity in concrete and indicate the extent to which steel is depassivated. The corrosion is linked to the presence of anodic and cathodic regions along the reinforcement, which causes variations in the electrochemical potential of the steel. These potentials are measured with a reference electrode attached to a voltmeter and the reinforcing steel. A schematic of the measurement is shown in Figure 2.10. Table 2.5 shows the interpretation of the Cu/CuSO<sub>4</sub> and Ag/AgCl rebar potentials.
- **Resistivity measurements** assess the concrete's ability to resist the passage of an electrical current. The 4-point Wenner probe is the most commonly used instrument to measure resistivity. It is determined by passing a small alternating current between the two outermost probes while the resulting potential difference is measured between the two innermost probes. A schematic of the measurement is shown in Figure 2.11. Table 2.6 shows the interpretation of the resistivity measurements in terms of corrosion risk.
- **Corrosion rate measurements** are the only quantitative measurements to assess the corrosion activity in reinforced concrete. The Linear Polarisation Resistance (LPR) technique can be used to determine the corrosion rate measurements using the relationship between the half-cell potential of corroding steel and an external potential or current applied to it. The measurements are obtained by either applying a small potential and measuring the resulting current response or applying a current and measuring the resulting potential response. Table 2.7 shows the interpretation of corrosion rate measurements.



**Figure 2.10: Schematic of the half-cell potential measurement (Alexander, et al., 2012)**

**Table 2.5: Rebar potentials and associated risk of corrosion (Alexander, et al., 2012)**

| Rebar potential (mV)           |                   | Qualitative risk of corrosion           |
|--------------------------------|-------------------|---|
| Cu/CuSO <sub>4</sub> electrode | Ag/AgCl electrode | Likely corrosion condition              |
| > -200                         | >-106             | Low (10% risk of corrosion)             |
| -200 to -350                   | -106 to -256      | Intermediate corrosion risk (uncertain) |
| < -350                         | < -256            | High (> 90% risk of corrosion)          |
| < -500                         | < -406            | Severe corrosion                        |



**Figure 2.11: Schematic of the 4-point Wenner probe (Alexander, et al., 2012)**

**Table 2.6: Resistivity measurements and associated risk of corrosion (Alexander, et al., 2012)**

| Resistivity (k Ω-cm) | Corrosion Risk Level  |
|----------------------|---|
| > 100 to 200         | Very low corrosion rate even if chloride contaminated             |
| 50 to 100            | Low corrosion rate  |
| 10 to 50             | Moderate to high corrosion rate                                   |
| < 10                 | High corrosion rate; Resistivity is not the controlling parameter |

**Table 2.7: Corrosion rate measurements and associated risk of corrosion (Alexander, et al., 2012)**

| Corrosion rate (µA/cm <sup>2</sup> ) | Qualitative assessment of corrosion rate |
|--------------------------------------|--|
| > 1.0                                | High                                     |
| 0.5 to 1.0                           | Moderate                                 |

| Corrosion rate ( $\mu\text{A}/\text{cm}^2$ ) | Qualitative assessment of corrosion rate |
|--|--|
| 0.1 to 0.5                                   | Low                                      |
| < 0.1  | Passive (negligible)                     |

## 2.5.2 Laboratory Testing

Core samples are extracted from concrete structures on site to provide more information on the type of deterioration they are experiencing. A powder sample can be obtained from a core sample to provide an estimate of the chloride contamination by assessing chloride profiles. A chloride profile is a graphical representation of the variation of the chloride concentration penetrating a concrete surface, which increases with time and decreases with depth. The profile is described using Fick's Law due to the dominating transportation mechanism being diffusion. However, near the surface, the profile does not follow the predicted shape due to the wetting and drying cycles. This zone is classified as the convection zone and the data points are ignored for fitting the curve profile (Alexander, et al., 2012). Figure 2.12 shows a typical chloride profile that has been fitted ignoring data points from the convection zone.

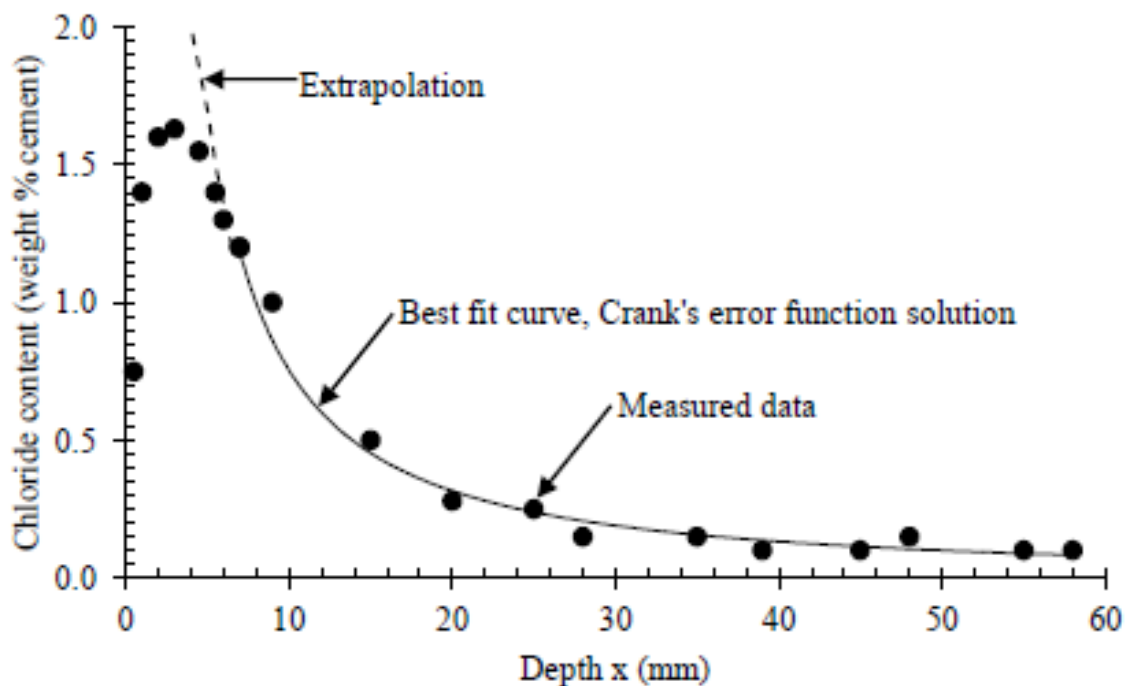
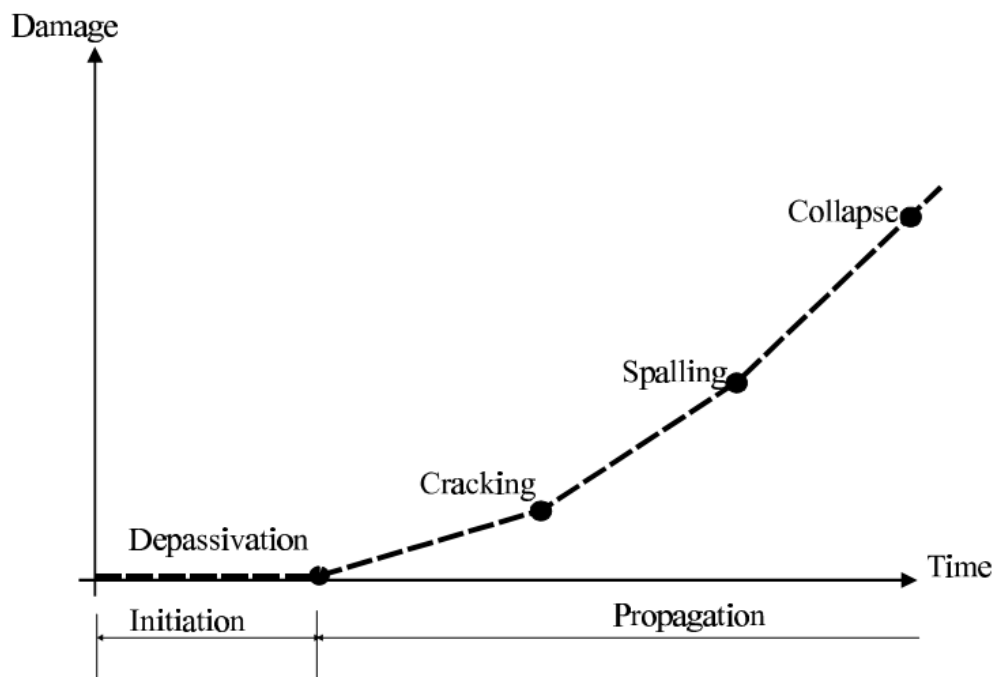


Figure 2.12: Typical chloride profile curve ignoring the convection zone (Alexander, et al., 2012)

Service life prediction models can be derived from parameters that can be assessed from chloride profiles. The chloride threshold, which is the concentration of chlorides required to depassivate steel and initiate corrosion, is used as an input parameter in the models. Factors such as the cover thickness, temperature, relative humidity and binder chemistry can affect the chloride threshold value. A conservative value to use is generally 0.4% of total chlorides by mass of binder. Using this value and other input parameters such as the concrete cover thickness and the diffusion coefficient from the chloride profile, service life prediction models such as DuraCrete can predict the duration to corrosion initiation or concentration of chlorides at a given time and depth. The DuraCrete model is based on two serviceability limit states, namely the depassivation of reinforcement and the cracking of the concrete, as well as two ultimate limit states, namely the spalling of the concrete cover and collapse. The serviceability limit states are related to durability while the ultimate limit states are related to both safety and durability (Siemes, 1999). Figure 2.13 shows the four durability limit states used by the DuraCrete service life model.



**Figure 2.13: DuraCrete service life model's durability limit states for reinforcement corrosion (Siemes, 1999)**

In addition to providing information regarding the service life of concrete infrastructure, a core sample can be used to provide further information. This includes visually assessing concrete cores to determine the concrete quality by analysing the constituents, voids, Alkali-Silica Reaction (ASR) signs, damage and reinforcement corrosion. Transport properties, density and strength can

also be determined through the measurement of parameters using the core sample (Beushausen & Louw, 2021).

## 2.6 Review of CMMS Software

Computerised Maintenance Management System (CMMS) software is one of the tools that can be used for managing the maintenance of infrastructure assets. It provides monitoring, tracking and analytical features. Users are able to view asset activities by creating a family tree that shows the connections between equipment, parts, components and their locations. Information related to cost, depreciation, warranties and claims is consolidated which assists with optimising the asset life. This makes the CMMS software useful for billing, invoicing, service history tracking and technician management (Windapo, 2020).

Further studies highlight the benefits of the application of CMMS software in infrastructure management. A systematic literature review by Dzulkipli, et al., (2021) discusses ways to improve building maintenance in Malaysia and recommended mitigation strategies. It recommends the use of CMMS software to:

- Reduce downtime,
- Minimise material and contractor costs,
- Easily assign work orders to technical teams,
- Create work requests and track their progress, and
- Track the entire lifecycle of an asset.

The review also recognises CMMS software as a reliable database to store data and monitor and measure the performance of services.

Another study by Majerník, et al. (2016) investigates measures to improve maintenance and reduce costs in a manufacturing company in the Czech Republic. It highlights the benefits of reducing paperwork as a contributor to improving the productivity of the company. These studies highlight the benefits of using CMMS software to manage infrastructure. However, both studies confirm that CMMS software does not provide maintenance decisions. Figure 2.14 summarises the functions of CMMS software.



**Figure 2.14: Functions of CMMS (Alshokry, et al., 2021)**

## 2.7 Digital Twin Technology for Asset Maintenance

Lind, et al. (2020) describe a Digital Twin (DT) as a dynamic digital replica of a system or an object, which uses a set of equations to describe its characteristics and properties. DTs leverage digital data streams, using both historical and real-time data, to minimise the gap between the physical object and its representation. This allows the digital twins to be analysed using situational parameters to produce possible outcomes for specific situations. They require continuous calibration throughout their lifecycle to ensure that they adhere to a constant model of reality.

DT technology can also be used for condition assessments by providing a detailed status of infrastructure. Defects can be identified by DT sensors, Internet of Things (IoT) and cloud computing and the advancement in Artificial Intelligence (AI) algorithms can assist with diagnosing the deterioration mechanism of a structure. This will assist in providing information for the mandatory condition assessments required by Ports. Predictive maintenance can also be conducted using DT technology data-driven techniques obtained from sensors or model-driven techniques which use mathematical methods to predict maintenance.

An infrastructure Digital Twin (DT) is the digital replica of an infrastructure which allows the real-time performance simulation of an asset. The physical object, its replica and the communication mode between the two are what define the digital twin. The benefits of the following factors are incorporated into digital twin technology (Mahmoodian et al., 2022):

- **Building Information Modelling (BIM):** An intelligent 3D model-based process which assists in visualising the performance of an infrastructure.
- **Sensors:** Enable real-time data to be collected and analysed.
- **Structural analysis methods:** Aim to simulate and analyse the structure.

A generic overview of the implementation of DT technology for the development of global smart ports is explored in research by Wang et al. (2021). The paper discusses the application of DT-driven management for improving cargo transportation, container storage, real-time data sharing, predictive optimisation and environmental sustainability. The following five steps are recommended for the successful implementation of DT-driven models in smart ports:

- **Step I – Data acquisition:** Historical and real-time data are required to create a virtual model and represent the different real scenarios encountered in smart ports.
- **Step II – Creation of a georeferenced model:** The 3D models need to incorporate smart ports' construction activities and interact with their built environments. Therefore, BIM is a recommended project delivery tool which will incorporate information throughout the smart port's lifecycle. The resultant georeferenced 3D model can provide data for the valid location of assets.
- **Step III – Integration of real-time information to the DT model:** To be able to forecast future developments and predictive maintenance and management, the DT model must receive real-time information. The physical layer plays a leading role through the model layer. Real-time information regarding Port Transportation and Operations (PTO) is uploaded from the physical layer to the data layer. This allows the DT model to update based on real-time PTO information continuously.
- **Step IV – Simulation, analysis and optimisation:** DT models must be used to simulate the design, execution, change and decommission lifecycle phases in the smart port process. This will assist with providing analytical results which will prevent erroneous decision-making, conduct preventative maintenance and reduce unpredictable accidents for PTOs.

- **Step V – Sharing and delivering insights:** The results obtained from the DT technology and models must be communicated through maps and dashboards to the relevant stakeholders. This allows decision-makers to make accurate and timely decisions, adding value for management and risk assessments.

Subsequent to the installation and implementation of sensors to commission DT models, it is imperative to ensure that the models are able to translate deterioration information into determining the service life of an asset. Research by Heng, et al. (2023) discusses the process and factors that determined the Remaining Useful Life (RUL) of wind turbine towers in the marine environment using a DT model. The DT model integrated a corrosion-fatigue model as well as a multi-physics model which incorporated the wind waves and climate. Sensors were placed on critical parts of a 10 MW floating offshore wind turbine to measure its deterioration due to corrosion fatigue. The evaluation of the corrosion fatigue was sectioned into three phases, namely, the cracking-driven force, crack size and crack growth rate. The crack growth rate was assumed to be controlled by the corrosion effect due to the limited crack size. An effective initial flaw size was calculated using a crack initiation limit and a crack growth threshold. Once a crack reached this size, the crack growth rate was assumed to be predicted by fracture mechanisms. Over time, the fatigue mechanism surpassed the corrosion effect until the final failure of the wind turbine component. The model was also designed to include a factor for the marine environment. This enabled the model to predict the service life of the components exposed to the marine environment based on three failure modes associated with the location of the sensors on the wind turbines. The dominant failure mode, which produced the lowest period, was used to predict the service life. This information was found to be useful in assisting asset owners with prioritising the maintenance needs of the critical components of the structure.

## **2.8 Case Study: Hamburg Port Authority’s (HPA) Köhlbrand Bridge**

One of the major challenges experienced by Hamburg in Germany is the condition of old bridges which are ageing and face increasing traffic volumes. The city requires efficient, safe and highly available infrastructure for its transport network to sustain a strong economy. To ensure that the bridges are well-maintained to meet the current demands, the city and the Hamburg Port Authority (HPA) saw a need to enhance the maintenance strategy of the port by launching the pilot project called “smartBRIGE Hamburg”, which is a digital twin of the Köhlbrand Bridge in Hamburg. The

bridge connects the eastern and western parts of the port. It was selected to test the concept of a digital twin for bridge maintenance due to its size, diversity and complexity (Wenner, et al., 2021). Figure 2.15 shows an image of the Köhlbrand Bridge in Hamburg.



**Figure 2.15: The Köhlbrand Bridge in Hamburg, Germany (Wenner, et al., 2021)**

The project monitors the structural condition of the bridge in real time to provide continuous monitoring of the maintenance strategy and its measures as well as to predict its future development. A better analysis of the damages experienced during maintenance can be provided by analysing data history. This can assist with ensuring that the best and optimum maintenance measures are implemented. In addition, the influence of changes in the maintenance strategy can be tracked, improved and optimised.

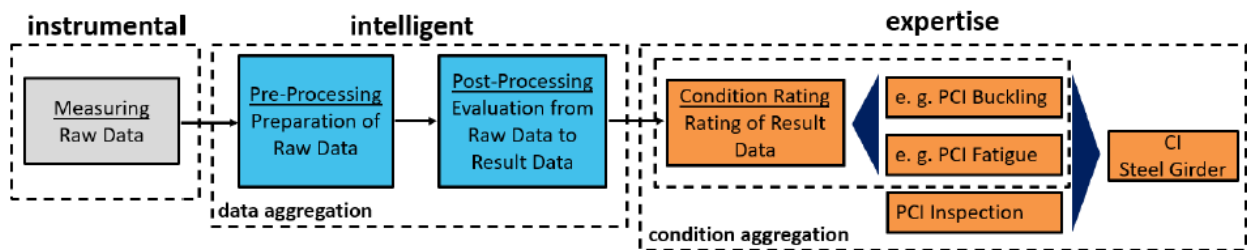
Wenner et al. (2021) identified the following five key points to realise the DT of the Köhlbrand Bridge to facilitate its maintenance:

- **Structural Health Monitoring (SHM):** SHM entails assessing an infrastructure’s health status using systems for sensing, processing and evaluation. This includes the monitoring of a structure and its components. To achieve this accurately, objectively and in real time, an asset requires well-selected and optimally-located sensors. A sensitivity analysis was performed for the smartBRIDGE Hamburg project to identify the critical parts of the structure that required monitoring to determine structural behaviour and detect changes.

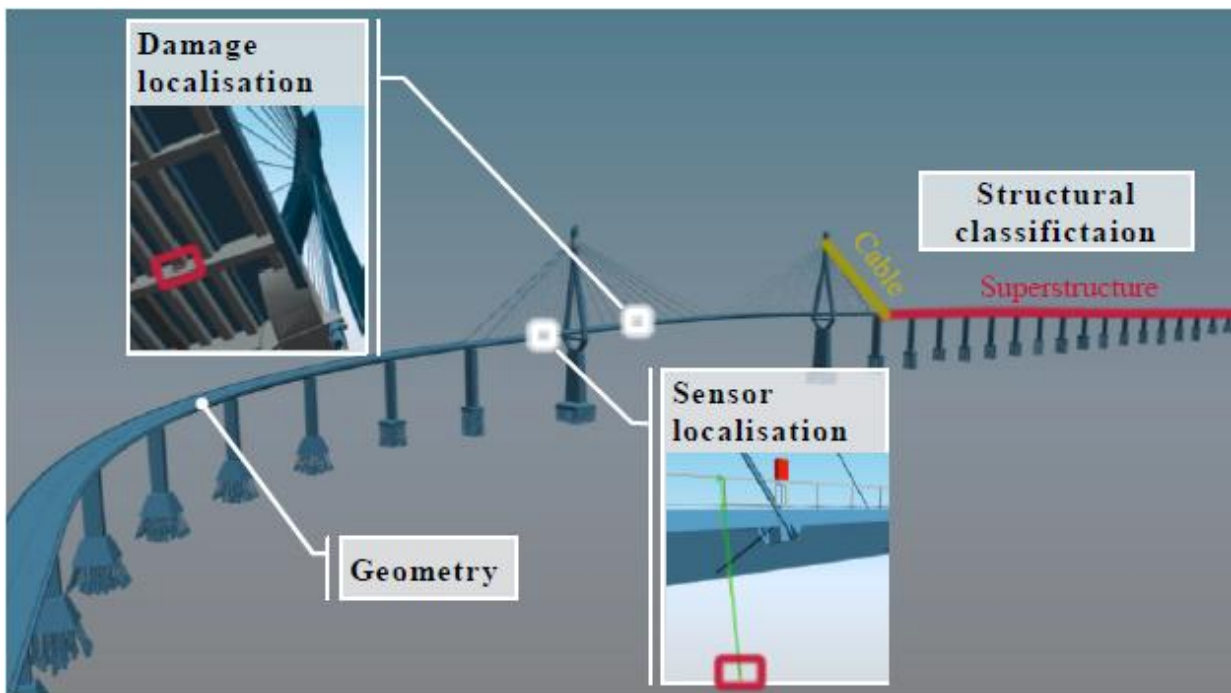
- **Aggregation of measurement data:** This step aimed to aggregate measured/raw data into consumable information and consisted of three main phases, which are summarised in Figure 2.16. The first phase consisted of measuring the raw data by using sensors to monitor existing damage, identify deterioration and predict the time for maintenance. The second phase consisted of using the sensor-based raw data and converting it into accessible structural indicators. Various partial indicators were developed to provide a condition evaluation of a structural component caused by various damage scenarios such as buckling and fatigue. A simplified rating can be used to classify the partial evaluations, e.g. from 1.0 (excellent condition) to 4.0 (severely structurally deteriorated). The smartBRIDGE project used Partial Condition Indicators (PCIs) which were classified into structural safety, traffic safety and durability. Lastly, the final phase consisted of consolidating the PCIs to provide a single rating value to indicate the condition of the structural component, i.e. the Condition Indicator (CI).
- **Combining conventional inspections and SHM:** To achieve an objective, complete and real-time evaluation of the Köhlbrand Bridge structure, cyclical inspections were conducted in parallel with the sensor monitoring evaluation. A similar rating system, which was accepted by engineers and asset owners, was used to obtain the PCIs and the CIs from physical inspections. These were combined to form the new PCIs and CIs which were consolidated and aggregated to incorporate both the physical and sensor evaluations. Improvements or optimisations to the maintenance strategy of the bridge were tracked using the final CI obtained for each component.
- **BIM for DT Realisation:** BIM visualises geometries and connects static information to produce 3D objects. For the Köhlbrand Bridge, BIM provided a basis for the bridge's DT by providing visual representations of the bridge's geometry, structural classification, damage localisation and sensor localisation. Furthermore, BIM generated information regarding condition indicators and structural damages and placed it in a temporal and spatial context. Figure 2.17 provides a summary of the uses of BIM within the DT of the Köhlbrand Bridge.
- **Human Machine Interface (HMI):** To enable the real-time accessibility of the DT information for the relevant stakeholders, a multi-level Human Machine Interface (HMI) is required. This enables the user to obtain the current infrastructure condition for any required structure and the extent of the deterioration. The conditionCONTROL interface

was the overall interface used for the DT realisation of the Köhlbrand Bridge. It uses the 3D model of the monitored structure to show geolocated key figures and contextually added data. The HMI provides a single point of accessing information on the DT. The related software for the interface includes WebGL, HMTL5 and Augmented Reality (AR) or Virtual Reality (VR) displays. This enables the interface to be more user-friendly, which makes it easier to provide information regarding the maintenance of the bridge to various stakeholders.

The key steps from the smartBRIDGE project provide a good guideline for how DT can be realised for the maintenance of an asset in the port environment.



**Figure 2.16: Summary of the aggregation process to classify the Köhlbrand Bridge CIs (Wenner et al., 2021)**

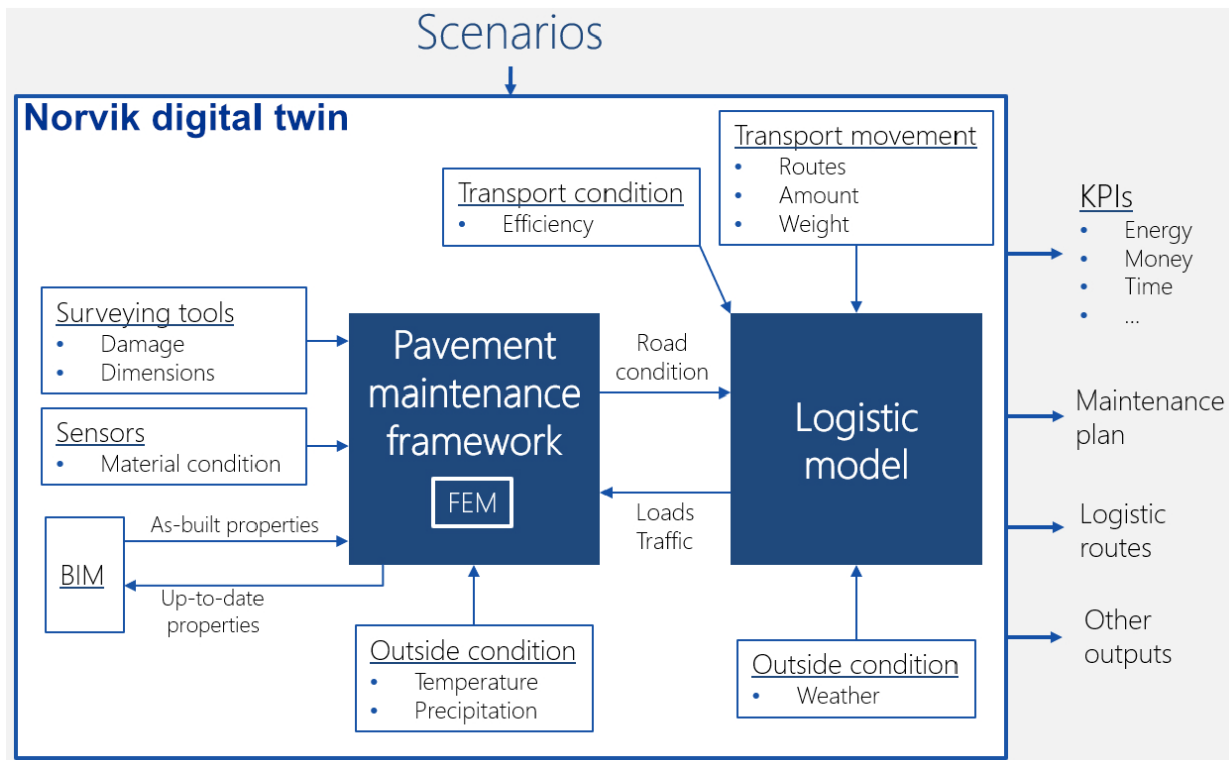


**Figure 2.17: Summary of BIM uses for the Köhlbrand Bridge’s DT (Wenner et al., 2021)**

## 2.9 Case Study: Norvik Port's Digital Twins

The city of Stockholm's Norvik Port is a new port located in the Baltic Sea in Sweden which consists of a container and an automotive terminal. Operations began in 2020 with plans to expand the capacity of the container terminal once it has reached its current capacity. The pavement areas in the port are used for terminal access, vehicle waiting zones and long-term parking for trailers. A doctoral thesis by Millan (2023) delves into the framework of a digital twin designed for Norvik Port. This innovative digital twin aimed to enhance pavement maintenance, thereby optimising the efficiency of the pavement and extending its lifespan. The DT model consists of two sections, namely the logistics model and the pavement maintenance framework. These sections interact and share information to iteratively provide an improved analysis. Input parameters into the model consist of sensors, pavement inspection tools, transport movements, load data, infrastructure usage and component locations. Figure 2.18 shows a schematic view of all the inputs that inform the Norvik Port's DT model.

The main benefit of the DT model developed for the Norvik Port's pavement maintenance framework is its ability to predict areas where stresses can appear in the pavement. This enables decision-makers to proactively predict the critical points of the pavement, which effectively reduces the port's downtime and allows operations to continue efficiently. Furthermore, the DT model allows possible alternatives of the pavement maintenance strategy to be tested and evaluated without interfering with its real-life physical counterpart. This scenario-based approach can identify improved and optimised potential strategies for minimising deterioration and disruptions to port operations.



**Figure 2.18: Input parameters for Norvik Port's DT model (Millan, 2023)**

The results of the Norvik Port's DT model analysis further benefit the decision-makers by providing information to extend the service life of the pavements. Different scenarios considering the logistic model, BIM, pavement field inspection results and the critical areas of the pavement around the port's terminals were analysed to provide an optimised pavement maintenance strategy. The Finite Element Model (FEM) approach was used in the DT model to accurately predict pavement deterioration in scenarios where traditional or historical data-based models are insufficient. This model approach enabled the port to develop different scenarios which included strategies for managing traffic flows and vehicle loads. The scenarios assessed the pavement deterioration according to different traffic paths, handover spots and the number of road uses from the logistic model. The consequences of the different scenarios were analysed to select a strategy that resulted in the least pavement damage to extend its service life while adhering to port operations.

## 2.10 Limitations of DT Technology for Smart Ports

The implementation of DT technology in smart ports can provide the following challenges (Wang et al., 2021):

- **Creating a mirrored DT model:** DT-based models for smart ports require the formulation of geometric and process information models to successfully formulate geometric

information, including the port environment, buildings, equipment, etc., which should be related to the actual port scene. Currently, the DT geometric modelling tools available are not intended to serve DT technology. Therefore, the modelling process requires 3D and parametric modelling by ensuring that a unique code is allocated to each modelling object. This implies that currently, the design of the basic process information model is not yet advanced for DT modelling.

- **Connection of DT data:** The consistency of scales, units of measurement, coordinates, etc. for the multi-dimensional and multi-scale data can be a limitation for achieving uniform data modelling. DT data can be lost during data collection or instruction processes. Additionally, in the process of traditional ports transforming into smart ports, the reliability and stability of wireless networks for data transmission cannot solely be relied on. Higher requirements are required for real-time DT-based model interaction. This also results in the large storage and processing required to handle the huge amount of data for DT-based models. Finally, one of the critical issues is finding a way to integrate and uniformly manage data from multiple sources in real time.
- **Securing data of DT systems:** A large amount of data regarding smart ports is generated and stored for DT-based modelling, including external data. Potential data leakage is possible once these storage forms encounter security problems, making critical smart port information vulnerable to external attacks.
- **Promoting ongoing DT application:** Potential application modes of DT for the reconstruction and integration of the port industry elements can be difficult to implement due to the continuous accuracy and verification required by DT-driven systems.

## 2.11 Future Work for DT Technology in Smart Ports

DT technology can be further incorporated into the port industry in addition to optimising port infrastructure maintenance. Cargo handling and transportation can be improved by using DT-based models to maintain cranes and other cargo-handling equipment. This will enable efficient operations and increase the productivity of terminal operators. Container terminal operations can be optimised by using a DT system to collect data and automate the container terminal. Proactive and informed decision-making can be enhanced by using DT-based models to predict scenarios before implementing changes to the operations. Data communication and sharing can be improved

using DT-based models to selectively share information in the smart port's transport chain, which enables a centralised platform for data sharing (Wang et al., 2021).

Although the additional applications of DT technology discussed above can be beneficial for other Transnet operational divisions, namely Transnet Port Terminals (TPT) and Transnet Corporate Centre (TCC), their limitations should be further explored prior to implementation. Further research investigating the implementation of DT technology in engineering (Botín-Sanabria, et al., 2022) has observed that DT implementation is currently limited due to the lack of standards, frameworks, regulations and recognised interactivity to monitor its implementation. In addition, the large number of sensors and computational resources required limits the implementation and accessibility of DT technology which makes it expensive to implement and monitor.

## **2.12 Summary and Discussion**

TNPA is responsible for the maintenance of waterside infrastructure such as breakwaters, dry docks, quays and other berthing structures and seawalls for the safe operations and navigation of the coastline around South African commercial ports. The TNPA AMPP manual provides guidelines regarding conducting condition assessments and rating the state of the waterside infrastructure. The condition assessment methods include the eyeball inspection, aerial survey, diving inspection and instrument measure (including cover assessments and salt ingress measurements). However, these are merely stated with no systematic guidelines on how they should be conducted. In addition, the asset condition ratings are based on a percentage grading system with no quantifiable parameters to inform the grading.

An assessment of the TNPA waterside infrastructure conducted by SAICE produced an overall grade of B minus, indicating well-maintained infrastructure meeting current demands. However, internal ratings of TNPA waterside infrastructure's condition range between 75.0 % and 76.2%, which is lower than the minimum target asset condition rating of 85% as per TNPA AMPP Manual recommendations. Other than these two assessments providing conflicting conclusions about the state of port infrastructure, the reliability of the SAICE IRC grading is also questioned due to its reliance on TNPA-provided information. This emphasises the need for an independent and objective rating system for a comprehensive understanding of the state of South African ports' infrastructure.

The primary challenge for the durability of concrete structures in the marine environment is reinforcement corrosion caused by chlorides, air, and water. While a passive oxide layer initially protects steel, ingress of chloride ions neutralizes it, leading to rust formation and subsequent issues such as cracks, reduced steel cross-sectional area and diminished bond between concrete and steel. Factors such as inadequate concrete cover depth, cracks, and porous concrete increase the risk of corrosion. Different marine zones, classified by exposure conditions, affect the severity of chloride ingress.

To ensure that condition assessments can determine the deterioration of concrete structures in the marine environment, testing methods should be able to adequately assess deterioration due to chloride ingress. The recommended surveys by Beushausen & Louw (2021) to find the location of the deteriorated concrete surface on site consist of a cover assessment and delamination surveys. After finding the weak locations, measurements can be conducted on site to determine the probability and rate of corrosion activity. These measurements consist of the half-cell potential, resistivity and corrosion rate measurements. Thereafter, sample cores can be extracted from the concrete structure to perform laboratory testing. This enables a detailed analysis of assessing chloride contamination through profiles. Parameters derived from chloride profiles contribute to service life prediction models, which can assist in indicating the remaining service life of the concrete structure. Core samples can also provide information on concrete quality, constituents, voids, signs of ASR, damage to the concrete matrix, and reinforcement corrosion, as well as transport properties, density, and strength.

The technology used for asset maintenance includes CMMS software and DT technology. CMMS software is used for tracking activities related to the maintenance of assets which assists with reducing downtime, tracking progress and assigning work orders to teams. DT technology involves creating dynamic digital replicas of systems or objects and utilising equations to describe their properties. The main limitation of CMMS software is its lack of providing maintenance decisions. This is the main advantage of DT technology used in asset maintenance, however, its implementation is challenged by requiring advanced tools, potential data losses, security concerns, the lack of standards, frameworks and regulations as well as high implementation costs.

Two case studies were discussed to provide insights into ports that have implemented DT technology for asset maintenance. For HPA's Köhlbrand Bridge in Germany, the "smartBRIGE Hamburg" pilot project was initiated to monitor the bridge's structural condition in real time,

provide continuous monitoring of the maintenance strategy and its measures and predict its future development. The project employs Structural Health Monitoring (SHM) to monitor the structure and its components. Condition Indicators (CIs) were obtained from both the sensors and conventional inspections to provide a consolidated CI. Interfaces such as BIM and AR or VR displays were used to enable infrastructure data to be shared using 3D models for various stakeholders. In the second case study, Stockholm's Norvik Port in Sweden employed a DT framework to enhance pavement maintenance efficiency. The model aided in extending pavement service life by assessing various scenarios considering logistics, BIM, pavement inspection, and critical areas around terminals. Both case studies demonstrate the effectiveness of digital twins in optimising infrastructure maintenance and performance. Further research by Wang et al. (2021) shows that DT technology can be adopted by ports to improve and optimise cargo handling and transportation, container terminal operations and data communication and sharing.

For successful DT-driven models in smart ports, five implementation steps are recommended, namely data acquisition, creation of a georeferenced model, integration of real-time information, simulation, analysis and optimisation, and sharing insights. Additionally, Heng et al. (2023) discuss using DT models for predicting the Remaining Useful Life (RUL) of wind turbine towers and integrating corrosion-fatigue and multi-physics models with sensors to measure deterioration. This information assists in prioritising maintenance for critical infrastructure components.

Given the highlighted considerations, a comprehensive assessment is important to evaluate TNPA's asset maintenance framework within the marine environment. The objective is to offer recommendations based on best practices adopted by international ports and global benchmarks. To achieve this goal, this research will focus on a case study involving the condition assessments of waterside infrastructure at the Port of Cape Town. The methodology to achieve the results using existing data is outlined in Chapter 3. The research will provide an understanding of asset maintenance challenges, strengths and areas for improvement for TNPA to enhance its overall maintenance strategy for marine infrastructure.

## 3 Methodology

This section outlines the methodology adopted in this research to reach the objectives. Existing infrastructure in both developed and developing countries tends to face neglect due to factors such as increased congestion, unnecessary operational costs and inadequate maintenance. To increase the longevity and productivity of assets, it is beneficial for the government to take advantage and make the best of its existing infrastructure to overcome increasing user demand, restricted financing and an ageing asset base (World Economic Forum, 2014). Based on this need, the World Economic Forum's Strategic Infrastructure Initiative and its Partners have developed a report which recommends the best practices for governments to operate and maintain their existing infrastructure assets. The three main aspects of operation and maintenance implementation strategies that should be adopted for asset operators are:

- Maximising the usage of an asset and improving the quality for users by increasing the utility of infrastructure.
- Minimising the total cost of infrastructure by reducing operating and maintenance costs and minimising the impacts of environmental and social impacts.
- Maximising infrastructure's value over its service life by reinvesting over its lifecycle.

This qualitative research is informed by guidelines in the abovementioned World Economic Forum's report, which aim to extend an asset's service life by developing a preventative and predictive maintenance strategy and avoiding and controlling excessive asset consumption and stress. The report also emphasises the need for the public sector to manage assets and control excessive consumption to mitigate risks. These are all key objectives that TNPA should strive to achieve for all its assets. The methodology adhered to is outlined in Sections 3.1 to 3.5 below.

### 3.1 Step 1: State the Analysis and Definition of Objectives

This step defined the research scope and finalised the aim, objectives and research questions in Chapter 1. The achievement of these objectives can assist with improving asset condition assessment methods and technology used in TNPA in the future.

### 3.2 Step 2: Data Collection

Condition assessment data was collected from existing TNPA databases to inform this research about asset maintenance in South African ports. The TNPA AMPP Manual, which is discussed in Chapter 2, provides insights into the current framework that informs the port authority in terms of conducting condition assessments for its port infrastructure inclusive of the guidelines, methodology, frequency, equipment/tools and software required. It also provides guidelines regarding rating asset conditions to provide information on the state of port infrastructure.

The TNPA AMPP Manual is used for asset maintenance by all TNPA ports. To assess the effectiveness of the manual for condition assessments in all ports, an in-depth assessment of one of the ports' condition assessment data will assist in determining if the guidelines for the condition assessment methods are being met by all ports and how they inform the asset condition rating of port infrastructure.

The data collected includes an extract of the asset condition rating sheet used by TNPA in Annexure A. This provides an understanding of how the overall asset condition rating is achieved for each waterside infrastructure and its sole reliance on the input of the assessor. The overall port asset condition ratings contained in Annexure B provide an overall state of the infrastructure for each port and allow one to compare their state amongst other Ports. This data was used to select the Port of Cape Town as a case study due to its low asset condition rating considering its asset base and revenue generated for TNPA. The Port of Cape Town's asset condition inspections between 2020 and 2023 were collected to analyse the TNPA AMPP Manual's maintenance methods used, the frequency in which the inspections were conducted, the recommended remedial measures as well as the corresponding asset condition rating that were obtained. Annexure C contains the summary of the inspection findings and Annexure D contains the asset condition assessment ratings for each of the Port of Cape Town's waterside infrastructure. These are used for providing the observations in Chapter 4. To analyse the current technology used by TNPA to improve or manage the maintenance of its infrastructure, the TNPA AMPP Manual was also analysed to understand the benefits and limitations of the SAP PM software used.

### **3.3 Step 3: Analyse the Current Asset's Condition and Assessment Methods**

To be able to provide the recommendations in Steps 4 and 5 below, a status quo analysis was conducted to evaluate the condition assessment records collected in Step 2 above. This entailed

determining if the condition assessments at the Port of Cape Town were conducted in accordance with the prescribed TNPA AMPP Manual for all waterside infrastructure. This is important to determine how effective the manual is in accurately diagnosing concrete deterioration in the marine environment and rate the state of the port infrastructure accordingly. Chapter 4 discusses the observations from the Port of Cape Town's condition assessment methods and frequency of inspections based on the data collected in Annexure C. The recommendations from these condition assessments are also analysed in informing the corresponding asset condition ratings in Annexure D from the inspections conducted. Furthermore, the effectiveness of these condition assessment methods in assessing chloride-induced deterioration is also explored in Chapter 4. The results of these analyses are crucial in addressing RQ1 and RQ2.

### **3.4 Step 4: Recommend Standardised Guidelines and Rating Systems for the Asset's Condition**

The World Economic Forum's report states that developing an effective maintenance strategy should include developing standardised metrics to assess an asset's condition. To determine if the TNPA AMPP Manual's current condition assessment methods are effective for determining chloride-induced concrete deterioration, a comparison is required with international best practices and guidelines. Section 4.5 compares these methods with the literature discussed in Chapter 2. The results of this comparison provided recommendations which will help improve the condition assessment methods for TNPA's waterside infrastructure.

The current TNPA asset condition rating used, as provided in Annexure A, is also compared with internationally used rating systems that can definitively determine the state of a concrete asset based on the size of the defects it is subjected to. A recommended rating system that TNPA can adopt is also provided in Section 4.5.

### **3.5 Step 5: Leverage technology for usage monitoring**

New technology is recommended for the continuous assessment of assets to improve deterioration detection (World Economic Forum, 2014). TNPA currently uses the SAP PM software to track asset maintenance activities. The full capabilities of this software as stated in the TNPA AMPP Manual are provided in Chapter 5. A gap analysis was conducted to compare the capabilities of this CMMS software with smart technology used by international ports for smart port maintenance

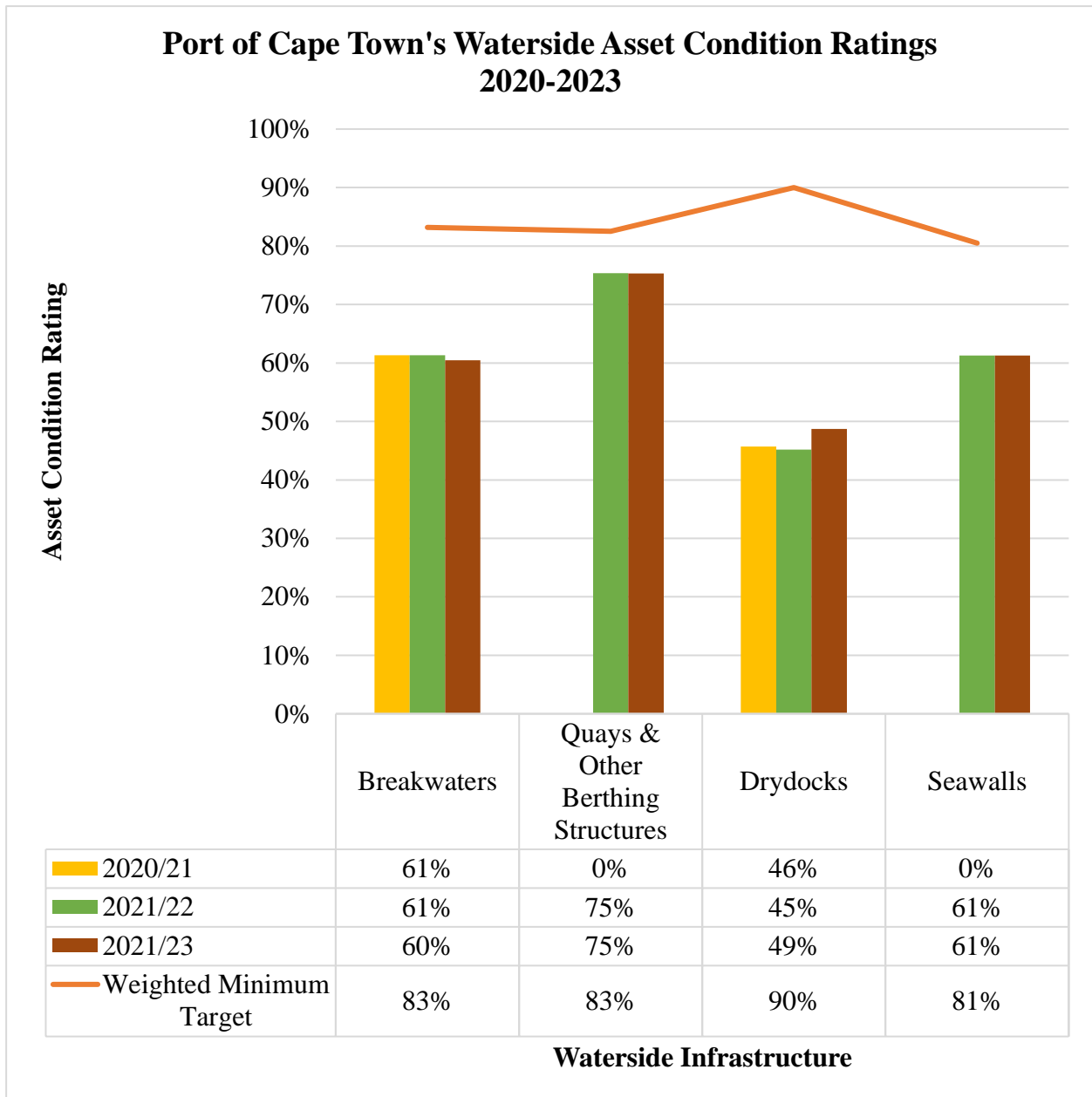
such as Hamburg Port Authority (HPA) in Germany and Norvic Port in Sweden, as discussed in Chapter 2. This comparison is discussed in Chapter 5 to provide recommendations that could be adopted and implemented by TNPA on how to implement this technology to improve the maintenance of its port infrastructure.

The methodology discussed in this chapter informs Chapter 4, where an analysis of TNPA's condition assessment guidelines was made using the Port of Cape Town as a case study. It also informs Chapter 5, where a comparative analysis was conducted between the technology employed by TNPA and that utilised by international ports.

## 4 Review of Condition Assessments at the Port of Cape Town

This section analyses the TNPA waterside infrastructure’s condition assessments conducted at the Port of Cape Town between 2020 and 2023 and recommends best practices for improvement. Findings from the port’s inspection reports regarding the inspection conducted and recommendations provided for each waterside infrastructure are summarised in Annexure C, and the detailed corresponding asset condition ratings from these inspections are provided in Annexure D. Figure 4.1 shows a summary of the Port of Cape Town’s asset condition rating with the weighted minimum target for each waterside infrastructure as provided in Annexure D. This was obtained by summing up the multiplication of the 85% minimum target asset condition rating of each asset’s item (e.g. outer armour, inner armour, outer toe, etc. for breakwaters) and their respective weight for the overall item. There are no asset condition ratings available for quays and other berthing structures as well as seawalls in the 2020/21 financial year due to the lack of resources available during the COVID-19 pandemic.

Ideally, the condition assessments for waterside infrastructure should be conducted annually using the prescribed methods as discussed in Section 2.2. These can be conducted by TNPA engineers and divers, except for the aerial survey for breakwaters which is conducted by CSIR. However, the latest damage assessment and aerial survey report by CSIR for the Port of Cape Town was provided in 2018. This is due to TNPA experiencing delays with a confinement between the port authority and CSIR. The aerial surveys will resume once the confinement has been approved. Therefore, the full scope of the waterside infrastructure’s condition could not be fully assessed at least once annually, as prescribed by the TNPA AMPP Manual, during 2020 and 2023. The observations of the type, frequency and recommendations of the condition assessments conducted for the Port of Cape Town’s waterside infrastructure are discussed in the subsequent sections.



**Figure 4.1: Summary of Port of Cape Town’s waterside asset condition ratings between 2020 and 2023 (Data supplied by TNPA)**

## 4.1 Breakwaters Inspections Observations

The Port of Cape Town’s Main Breakwater has three sections, namely the spur, trunk and vertical wall. There are also two secondary breakwaters located at A-Berth and Eastern Mole. The Eastern Mole breakwater does not form part of the inspections due to damage caused by a vessel in 2018. The port’s inspection reports state that its repair will be considered separately. An aerial view of the Main Breakwater is provided in Figure 4.2 below. All three breakwaters at the port consist of concrete units that are in the airborne, tidal, splash and spray, and submerged zones.



**Figure 4.2: Port of Cape Town's Main Breakwater (Picture supplied by TNPA)**

The TNPA AMPP Manual prescribes that the eyeball inspection and aerial survey by CSIR should be conducted at least once annually for breakwaters. The Port of Cape Town's breakwater condition assessments between 2020 and 2023 in Annexure C1 show that the breakwaters have been assessed each year using the eyeball inspection. This implies that the aerial survey was the only outstanding inspection method during this period. During the 2021/22 financial year, the port improvised by conducting a diving inspection for the absence of the aerial survey to assist in providing a condition assessment for submerged breakwater units. Although an effort was made by the port team to make up for the lack of information from the aerial survey, this alternative provided limited information. The diving inspection provides a visual condition assessment of the breakwater units, while the aerial survey not only offers a visual condition assessment but also provides information regarding the horizontal and vertical displacements of the breakwaters' overall armour protection.

The comments/recommendations from the inspection reports in Annexure C1 state that "more damage" has been observed from 2021 to 2023 at the trunk of the main breakwater. However, no further detailed explanations have been provided regarding the "damage" observed. This is a recurring comment provided by the team without any further recommendation on possible mitigation or rehabilitation actions that could be provided for the future. In addition, there are no quantifiable measures to make note of this and to assess the deterioration of the breakwater units further. The asset condition rating of 61% between 2021 and 2023 implies that the breakwaters are in a good to fair condition, although no quantifiable measures are provided to confirm this rating. This contradicts the "more damage" noted in the comments without further descriptions or

explanations while the asset condition ratings remain similar. The lack of instrument measures prescribed for the condition assessment in the TNPA AMPP manual is a contributor to this problem. It is unclear if these observations are based on actual further concrete deterioration, such as cracking, reinforcing steel corrosion, erosion, spalling, pop-outs, scaling, etc., or the inspector's bias.

## 4.2 Dry Docks Inspections Observations

The port has two dry docks, namely the Sturrock and Robinson Dry Docks. The condition assessment includes items such as the pump house, service tunnels and valve chambers. However, this report only discusses the asset condition assessment of the concrete structure, i.e. the main graving dock. Figure 4.3 shows a section of the Robinson Dry Dock from the 2021 inspection report.



**Figure 4.3: Robinson Dry Dock at the Port of Cape Town (Picture supplied by TNPA)**

The TNPA AMPP Manual prescribes that the eyeball inspection and the instrument measure method should be conducted at least once annually for dry docks. Annexure C2 shows that the

concrete structures of the dry docks have only been assessed using the eyeball method between 2020 and 2021. TNPA attributed this to the lack of resources in terms of staffing and maintenance experienced by the Port of Cape Town in the SAICE 2022 IRC. This implies that the instrument measure method has not been conducted during this period. Therefore, the inspections and corresponding asset condition ratings provide an incomplete assessment of the Port of Cape Town dry docks.

The comments/recommendations of the inspection reports in Annexure C2 described the condition of the dry docks as “severely deteriorated” and recommended that a capital project address it. There are no further descriptions to describe the concrete deterioration observed, such as cracking, reinforcing steel corrosion, erosion, spalling, pop-outs and scaling. These would provide a better understanding to justify why a capital project is required to address it. The asset condition ratings ranging between 46% and 49%, which is fair and poor respectively, seem to correspond to the comments. Therefore, the dry docks appear to have been accurately assessed using the eyeball inspection method. However, the lack of the instrument measure method does not inform or justify the asset condition rating provided. The rating would have been considered to be accurate and objective if there were quantifiable deterioration measures to inform the concrete deterioration observed. This would have also provided motivation for the expedition of a capital project required to rehabilitate the state of the dry docks. This recommendation is currently based on a subjective assessment.

### **4.3 Quays and Other Berthing Structures Inspections Observations**

The quays and other berthing structures are combined into one inspection report. The 41 berths are grouped into 33 structures in the report. This includes the assessment of the founding structures such as the sheet pile walls (both above ground and submerged), as well as the surface slab. Figure 4.4 shows a section of the M-Berth quay wall at the Port of Cape Town.

The TNPA AMPP Manual prescribes that the eyeball inspection, diving inspection and instrument measure methods should be conducted at least once annually for quays and other berthing structures. The Port of Cape Town has a total of 41 quays and other berthing structures. Annexure C3 shows that the assets were not assessed in the 2020/21 financial year. The only assessment method that was conducted for the inspections was the eyeball inspection between 2021 and 2023. This implies that both the instrument measure and diving inspection methods were not performed

during the 2020 to 2023 period. However, it has been noted that the diving inspection method was conducted for the Port of Cape Town’s breakwaters during the 2021/22 financial year even though this method is not prescribed for breakwaters in the TNPA AMPP Manual. Therefore, the port does not adhere to the currently recommended inspection methods for the quays and other berthing structures.



**Figure 4.4: Port of Cape Town’s quay wall section at M-Berth (Picture supplied by TNPA)**

The comments/recommendations of the inspection reports in Annexure C3 regarding the deterioration of the structures are similar and have minor amendments between 2021 and 2023. Most note that longitudinal cracks have formed and the recommendation states that the cracks must be monitored. There is no additional information provided regarding the cracks such as the crack width and length, which could assist with classifying its origin. In addition, the overall asset condition rating remains at 75% between 2021 and 2023, which is considered to be a good condition. This is not informed by any quantifiable measures, and the longitudinal cracks noted may contradict the “good” condition provided. Furthermore, the 2022 report contains a section of Jetty 1 where a severely spalled quay edge is considered to be in “good condition” with “minor spalling”. The report did not have any recommendations for this defect. Figure 4.5 shows an extract of this report with a picture of the spalled quay edge. The spalled concrete section appears to be approximately 250 mm in length. It seems unstable with further spalling anticipated. This classification of the asset’s condition is inaccurate considering the safety concerns which could

affect both the port personnel and vessels or equipment during berthing operations if this spalled section was to disintegrate. An asset condition rating below 20% would have been more accurate to show the severity of this defect. Also, the only recommended action for most of the cracks that have been observed, regardless of length and width, is to “monitor” them, which is not ideal. This proves that the ratings are subjective based on the opinions of the assessor. The lack of instrument measure parameters also contributes to the lack of evidence for the good asset condition ratings and descriptions.

### 3.21 Jetty 1

Jetty 1 is mostly in a good condition. There are minor spalling leaving aggregate exposed. There are also cracks at the capping and walls.



Figure 49: A piece of loose concrete along the cope edge

Figure 4.5: Extract of the inaccurately described Jetty 1 condition at the Port of Cape Town (Picture supplied by TNPA)

## 4.4 Seawalls Inspections Observations

The seawall inspection reports consist of the assessments of seawalls, revetments and other coastal protection structures combined into one report. Most of the Port of Cape Town’s seawalls consist of closed-type stone pitched overlain with concrete units such as those used for breakwaters, i.e. dolos. The aerial survey report provided by CSIR typically also includes a damage assessment for these coastal protection structures. Figure 4.6 shows a seawall overlain with rocks and concrete units at the Port of Cape Town.

The TNPA AMPP manual prescribes that the eyeball inspection, diving inspection and instrument measure methods should be conducted at least once annually for seawalls. Annexure C4 shows that the seawall condition assessment did not take place in the 2020/21 financial year, while only

the eyeball method was used between 2021 and 2023. This implies that the asset condition rating is provided without the instrument measure and diving inspection methods, which indicates that the port did not adhere to the minimum condition assessment requirements as per the TNPA AMPP Manual.



**Figure 4.6: Seawall at the Port of Cape Town (Picture supplied by TNPA)**

Excessive erosion has been noted in the comments/recommendations of the inspection reports in Annexure C4, particularly for the A-Berth seawall between 2021 and 2023 using the eyeball inspection. Figure 4.7 shows a section of the A-Berth seawall with excessive erosion. The comments further state that the seawalls cannot serve their main function of coastal protection and that urgent repair is required. Although a diving inspection, laser scan and aerial survey have been requested each year between 2021 and 2023 to provide further detailed condition assessments for the seawalls at the Port of Cape Town, these have not been executed due to resource constraints with the diving inspection team. The overall seawall asset condition ratings of 61% imply that they are in good to fair condition. However, this is not justified considering the comments regarding the failure of the seawalls to perform their main coastal protection function. A rating of 0 to 10% would be more accurate to highlight the risks associated with a lack of coastal protection, especially during high tides. Furthermore, the additional inspection methods requested should be conducted to provide a more holistic condition of the asset. Therefore, not only are the TNPA

AMPP Manual inspection methods insufficient to determine the holistic condition of the asset, but the corresponding asset condition ratings do not reflect the comments that have been repeatedly stated each year.



**Figure 4.7: Excessive erosion on a seawall section at the Port of Cape Town (Picture supplied by TNPA)**

## **4.5 Recommendations for Best Practices**

### **4.5.1 Condition Assessment Methods for the Marine Environment**

The observations in Sections 4.1 to 4.4 above show three main challenges experienced with the condition assessment of waterside infrastructure at TNPA using the Port of Cape Town as a case study. To begin with, the minimum number of condition assessment methods stipulated in the TNPA AMPP Manual was not adhered to for each type of waterside infrastructure. Resource constraints have been highlighted by TNPA to be the main challenge. In addition, there have been inconsistencies with applying existing condition assessment methods for the correct waterside infrastructure as stated in the TNPA AMPP Manual. Finally, from the condition assessment methods that were conducted, the comments and recommendations noted did not align with the severity of the deterioration witnessed on site. This proves that there is a lack of adequate condition assessment strategies to assess the deterioration of concrete assets in the marine environment due to chloride ingress. The eyeball method, which was conducted on all assets, does not have set guidelines to align the size of the defects observed with the asset condition rating, which resulted in subjective asset condition ratings that were not informed by quantifiable parameters. Although the TNPA AMPP Manual recommends that cover surveys and salt ingress measurements are part of the instrument measure method, no clear guidelines are provided regarding how these should

be conducted and how the results can be used to determine the remaining service life of the waterside infrastructure. An impartial and credible evaluation is important for a comprehensive and accurate understanding of the condition of SA ports in comparison to international ports.

To ensure that TNPA's condition assessment methods effectively assess deterioration due to chloride ingress for all types of waterside infrastructure, the following amendments are recommended as guided by the literature review in Chapter 2:

- **Eyeball method:** This method, which can be considered as a visual assessment, should be the first method conducted for all waterside infrastructure. It should be conducted using key instrument measurements such as crack measurements using a crack ruler, cover assessments using a cover meter and delamination surveys using a hammer. The size of the crack in terms of its width and length should be provided using length units to provide an indication of the severity of the asset's deterioration. An example of a crack ruler that can be used for the eyeball method is shown in Figure 4.8. The cover assessment and delamination survey will be able to identify weak areas in the concrete structure based on areas that do not have sufficient cover for the marine environment (i.e. 60 mm) and areas with spalling concrete. These areas will be subject to further assessments as per the amended instrument measure method below.
- **Instrument measure:** This method should be conducted after the eyeball method on weak areas that have been identified. The information that should be obtained consists of conducting half-cell potential, resistivity and corrosion rate measurements. These will assist with indicating the probability and strength of the corrosion activity. Thereafter, cores can be extracted to perform chloride profiling where the concrete cover depth will be plotted against the chloride content. This graphical representation and information from the structure's cover assessment will be crucial to determine whether the reinforcing steel has been depassivated or not based on the chloride threshold content. Lastly, service life prediction models such as DuraCrete will be able to plot the damage with time to indicate the structure's service life, which is an estimation of the time period over which it can serve its purpose without reaching its durability and serviceability limit states.
- **Diving inspection:** This method should continue to be conducted for assessing the toe integrity, scour protection and prop-wash for quays and other berthing structures as well as seawalls. In addition, it should also be conducted to visually assess concrete damage, as

per the eyeball method, for inaccessible concrete structures such as those located in the splash/spray, tidal and submerged zones. The instrument measure method can be conducted if further assessment is required.

- **Aerial survey conducted by CSIR:** This survey can continue to be conducted mainly for breakwaters since it provides information on the overall alignment of the breakwater units, as well as the damage and displacement of the armour protection, which cannot be achieved by the above methods. The deterioration of the concrete units located in accessible areas can be assessed using the eyeball and instrument measure.



**Figure 4.8: Example of a crack ruler for the eyeball method**

According to Beushausen & Louw (2021), the implementation of these amendments above must be led by an experienced engineer with knowledge of structural design and materials technology.

To limit the resource constraints experienced by TNPA, the type and frequency of condition assessments must be optimised. Table 4.1 below provides a recommendation for the frequency of condition assessment methods mentioned above that can be adopted by TNPA for all waterside infrastructure.

**Table 4.1: Recommended frequency of condition assessments for waterside infrastructure**

| Condition<br>Assessment Method    | Instruments/Tools<br>Required  | Deterioration measured<br>or assessment  | Frequency   |
|-----------------------------------|--|--|---|
| Eyeball (or visual)<br>inspection | <ul style="list-style-type: none"> <li>• Crack ruler</li> <li>• Cover meter</li> <li>• Hammer</li> </ul>   | <ul style="list-style-type: none"> <li>• Defects (cracks, spalls, pop-outs, erosion, etc.)</li> <li>• Cover assessment</li> <li>• Delamination survey</li> </ul> | Annually  |
| Instrument measure                | <ul style="list-style-type: none"> <li>• Half-cell potential equipment</li> <li>• Wenner probe</li> <li>• Liner Polarisation Resistance (LPR) equipment</li> <li>• Chloride profiling laboratory set-up</li> </ul> | <ul style="list-style-type: none"> <li>• Half-cell potential</li> <li>• Resistivity</li> <li>• Corrosion rate</li> <li>• Chloride profiling</li> </ul>           | Every 3 to 5 years depending on resource availability |
| Diving inspection                 | Diving equipment   | Defects  | Every 2 to 3 years depending on resource availability |
| Aerial survey conducted by CSIR   | CSIR equipment   | Horizontal and vertical alignment of concrete units and damage or displacement of the armour protection  | Every 2 to 3 years depending on resource availability |

#### 4.5.2 Standardised Asset Condition Rating

The need for TNPA to adopt a standardised asset condition rating that is linked to the size of concrete defects has been identified from the Port of Cape Town’s condition assessment observations. Clear and objective guidelines, aligned with international best practices, must inform the determination of the rating. Common concrete defects include cracking, surface damage, surface discolouration, joint deficiencies, member shape changes and textural features. These can be identified during the amended eyeball inspection method in Section 4.5.1. A damage

classification system, such as the example provided by Beushausen & Louw (2021), can be adopted by TNPA due to its clear relationship between the size of concrete defects and the damage rating. The recommended damage classification is shown in Table 4.2. This rating system can be incorporated into the current TNPA rating sheet in Annexure A for condition assessments using the eyeball inspection method. This clear guideline can eliminate subjective ratings and provide standardised ratings for TNPA’s waterside infrastructure which can be uniformly communicated with various stakeholders such as SAICE.

**Table 4.2: Damage classification of defects (Beushausen & Louw, 2021)**

| Damage  | Damage Rating      |                      |                   |   |   |
|---|--------------------|----------------------|-------------------|---|---|
|   | 1 (Very Slight)    | 2 (Slight)           | 3 (Moderate)      | 4 (Severe)  | 5 (Very Severe)                                   |
| Cracks in prestressed concrete due to overloading | Width < 0.05mm     | Width 0.05 – 0.1mm   | Width 0.1 – 0.3mm | Width 0.3 – 1mm                                   | Width 1 – 3mm with some spalling                  |
| Cracks in reinforced concrete due to overloading  | Width < 0.1mm      | Width 0.1 – 0.3mm    | Width 0.3 – 1mm   | Width 1 – 3mm                                     | Width > 5mm                                       |
| Cracks in unreinforced Concrete                   | Width < 1mm        | Width 1 – 10mm       | Width 10 – 20mm   | Width 20 – 25mm                                   | Width > 25mm with widespread spalling             |
| Shrinkage or settlement cracks                    | Single small crack | Several small cracks | Many small cracks | Few large cracks                                  | Many large cracks                                 |
| Effects of reinforcement corrosion                | Barely noticeable  | Light rust stains    | Heavy rust stains | Heavy rust stains and cracking along line of bars | Heavy rust stains and spalling along line of bars |
| Pop-outs  | Barely noticeable  | Clearly noticeable   | Holes ≤ 10mm Ø    | Holes 10 – 50mm Ø                                 | Holes ≥ 50mm Ø                                    |

|          |                   |                    |                              |                      |                      |
|----------|-------------------|--------------------|------------------------------|----------------------|----------------------|
| Spalling | Barely noticeable | Clearly noticeable | Larger than coarse aggregate | Areas ≤ 150mm across | Areas ≥ 150mm across |
|----------|-------------------|--------------------|------------------------------|----------------------|----------------------|

## 5 Review and Assessment of the TNPA Asset Maintenance Technology

This section discusses the benefits and limitations of the technology currently used by TNPA for its infrastructure maintenance. It also recommends technology used by smart international ports for the maintenance of their infrastructure and how this technology can be adopted in TNPA.

### 5.1 TNPA SAP PM Software

TNPA uses the SAP PM software to track all asset condition assessment activities. The Maintenance Manager is responsible for ensuring that maintenance regimes are created on SAP PM for all maintainable assets. The Port Engineer, whom the Maintenance Manager reports to, must ensure that there is alignment between the Financial Asset Register (FAR) and the SAP master sheet (Transnet National Ports Authority, 2016). One of the key pieces of information contained in the FAR for assets is the Remaining Useful Life (RUL) which helps an organisation to determine its capital renewal needs, priorities and forecasts. The age and condition of an asset are the main contributors to an asset's RUL (Windapo, 2020).

Prior to using SAP PM, the following activities are performed by the maintenance department in each port:

- Assessing the work required and determining the maintenance requirements of each asset.
- Determining the resources required and compiling a personnel structure.
- Compiling the monthly cash flow and compare it with the approved budget.
- Prioritising maintenance tasks.
- Compiling the maintenance schedule.

The following activities are then performed on the SAP PM software:

- Loading of inspection frequencies through detailed task lists assigned to maintenance plans.
- Integration of asset condition monitoring schedules to display the overall condition of assets in each port.

- Creation of maintenance plans for all maintainable assets that require recurring maintenance or inspections. This includes planned work arising from the recurring inspections.
- Adjustments to the schedules to allow prioritisation of unscheduled work. All unplanned work must first be approved by the relevant delegation of authority with the necessary budget before execution starts.
- Closure of work orders including notifications regarding breakdown duration, damage and cause.

## 5.2 Observations

The SAP PM software benefits TNPA by providing a centralised database for managing maintenance-related information. It enables the organisation to track the maintenance activities and condition of assets. It also enhances the effective use of resources and allows better workforce planning since trends, peak maintenance periods and resource requirements can be extracted from the software. The alignment of the software with the procurement and finance departments also assists with communicating accurate maintenance information at all times, which improves the timely resolution of maintenance issues.

Despite the capabilities to track maintenance activities and asset conditions, the SAP PM software has a few limitations. One of the main restrictions is its lack to autonomously make maintenance decisions and provide an asset's condition status, which still relies on the expertise and decision-making capabilities of the port engineering resources. The software also cannot independently determine when maintenance should be performed for an asset. The maintenance requirements are determined upfront by the team. This limits the software's ability to assist with the forecasting and planning elements of maintenance. Furthermore, there is currently no autonomous manner to obtain the remaining service life of a structure or asset using the SAP PM software. This information requires manual calculations and is loaded onto the software to align with the FAR.

Considering the SAP PM software's benefits and limitations, it is crucial for TNPA to consider technologies that can autonomously make maintenance decisions and provide an indication of when maintenance is required for assets as well as their remaining service life. Proactive software can assist with alleviating resource restrictions and prioritising maintenance requirements for severely deteriorated assets.

### 5.3 Recommendations for Best Practice

The observations above emphasise the need for TNPA to adopt smart technology to assist with making maintenance decisions. The literature in Chapter 2 has demonstrated how international ports are using advanced technology to maintain their infrastructure and achieve smart port maintenance. Research by Lind, et al. (2020) described how DT technology creates a digital representation of an asset and allows situational parameters to be analysed using historical and real-time data. Sensors placed on the asset can identify defects to assist with diagnosing the deterioration of a concrete structure. The condition of an asset's deterioration can be obtained by using a consolidated condition indicator from a DT model and conventional inspections, as evidenced by the smartBRIDGE Hamburg pilot project. These condition indicators can be modified to incorporate the concrete defect classification rating, such as the example provided by Beushausen & Louw (2021), to ensure that the ratings obtained from the DT model are standardised. In addition, the DT model can be modified to consider deterioration from the marine environment as per the research by Heng, et al. (2023). The DT models can benefit TNPA by autonomously providing information such as the remaining service life of critical assets and can also assist with optimising maintenance strategies and port operations using scenario analyses, as evidenced by Norvic Port's DT model. This information will assist with allocating and scheduling resources for the maintenance of port infrastructure. The asset condition information obtained from this model can be directly shared with various stakeholders using 3D models on AR or VR displays to minimise misinterpretation of condition assessment results.

Although the benefits are crucial, DT technology limitations regarding, amongst others, securing data, high implementation costs and lack of standards and frameworks must also be further explored and taken into account prior to implementation.

The capabilities of the current SAP PM software can be evaluated to provide a gap analysis with DT technology. The implementation steps from the study by Wang et al. (2021) exploring the development of global smart ports are used for the comparison. Table 5.1 shows the comparison between the current TNPA SAP PM software and the recommended implementation steps for DT technology. The gap analysis shows that for TNPA to have functioning DT models, the installation of the BIM software and sensors that assess deterioration are the main stumbling blocks required for the port authority to successfully implement this technology.

**Table 5.1: Gap analysis between SAP PM and DT technology implementation steps**

| DT Technology Implementation Steps               | Possibility for TNPA to adapt based on SAP PM capabilities (Yes/No) | GAP Analysis  | Comments  |
|--|---|---|---|
| 1. Data acquisition                              | Yes   | None  | The SAP PM software already requires data to be pre-loaded. TNPA currently has a central database containing all asset condition information. |
| 2. Creation of a georeferenced model             | No  | The BIM software is required to provide the georeferenced model.          | TNPA would need to install and use BIM for maintenance projects. SAP PM is ineffective for this.  |
| 3. Integration of real-time information to model | No  | Sensors are required to communicate infrastructure and overall port data. | TNPA requires the installation of sensors that can assess deterioration in real time.   |
| 4. Simulation, analysis and optimisation         | No  | Sensors and BIM are required to execute the DT model.                     | This step can only take place once Steps 2 and 3 are implemented.   |
| 5. Sharing and delivering insights               | Yes   | None  | TNPA already can share project information through current interactive dashboards such as Microsoft's Power Business Intelligence (BI).       |

Considering the major obstacles that prevent TNPA from implementing DT technology for smart maintenance immediately, the optimisation of the current SAP PM software is required. The frequency of the condition assessments of the waterside infrastructure can be modified to include the recommendations provided in Table 4.1. This can be linked with the instruments/tools

required to conduct each assessment method as well as the personnel required. In addition to assisting in the management of maintenance activities, these amendments will ensure that the condition assessments conducted effectively assess chloride-induced deterioration. Furthermore, the service life prediction results from the chloride profile can be used to estimate the RUL more accurately, which will then be used to update the FAR.

## 6 Conclusions and Recommendations

The research investigated the challenges with the current asset condition assessments for waterside infrastructure in TNPA and provided recommendations on how to improve the current asset condition methods, rating and software.

The literature review provided insights into the state of TNPA's port infrastructure, its guidelines for waterside asset condition assessments, knowledge of effective tests addressing chloride-induced deterioration as well as smart technology adopted by international ports to improve the maintenance of their infrastructure. The national assessment of port infrastructure provided by TNPA and shared with SAICE shows that the condition of TNPA's infrastructure is not objective due to the varying results based on the stakeholders. The condition assessment methods of waterside infrastructure include the eyeball inspection, diving inspection, aerial survey and instrument measure methods. These are prescribed to be conducted annually by the TNPA AMPP Manual. The corresponding asset condition rating for these condition assessments uses a percentage grading system with no link to the size of the concrete defects or deterioration observed. For concrete structures in the marine environment, the key in-situ tests that are recommended to identify the probability and strength of chloride-induced deterioration include cover assessments, delamination surveys and measurements of the half-cell potential, resistivity and corrosion rate. Further laboratory tests include analysing chloride profiles which can provide predictions of the remaining service life of a structure using service life prediction models. In addition, smart technology can be implemented to autonomously provide remaining service life predictions and optimise the maintenance strategies of ports using DT technology models, as used by the HPA in Germany and Norvic Port in Sweden.

The observations concluded that not all the prescribed condition assessment methods were conducted for the waterside infrastructure at the Port of Cape Town between 2020 and 2023. The minimum frequency of asset condition assessments as recommended in the TNPA AMPP Manual was not adhered to by the Port of Cape Town, in addition to using condition assessment methods not prescribed for each waterside infrastructure. The asset condition ratings relied solely on observations obtained from the eyeball inspection method without information on how the holistic infrastructure, inclusive of sections located in the tidal and submerged zones, is deteriorating. Further analysis of the comments from the inspection reports indicates that there is no systematic

guideline to align the defects observed on the concrete structures on site to the asset condition rating. Therefore, the current asset condition assessment ratings are subjective and potentially provide a misleading narrative of the state of port infrastructure. This is also evident in the varying port infrastructure condition ratings provided by TNPA and SAICE. Therefore, to address RQ1, using the Port of Cape Town as a case study, the main challenge regarding TNPA maintaining its waterside infrastructure is its failure to conduct the minimum amount of holistic asset condition assessments annually and its lack of clear guidelines to provide objective asset condition ratings. An example of a guideline by Beushausen & Louw (2021) can be adopted by TNPA since it shows how the concrete defects observed can be measured and aligned to inform the asset condition ratings. This guideline could be incorporated into the current TNPA asset condition rating sheet provided in Annexure A.

The research also looked into the effectiveness of the prescribed TNPA condition assessment methods concerning addressing chloride-induced deterioration for concrete structures in the marine environment. The instrument measure method in the TNPA AMPP Manual is prescribed for all waterside infrastructure except for the breakwater assessments. Although it mentions important condition assessment measures such as cover assessment and salt ingress measurements, these are only stated as one-liners with no clear guide on how they should be conducted. There is also no mention of how information from these assessments can be used to provide key information such as the remaining service life of the waterside infrastructure. Therefore, to address RQ2, it is evident that the current condition assessment methods in the TNPA AMPP Manual fall short of meeting guidelines for evaluating the deterioration of concrete structures in marine environments. To effectively assess deterioration taking chloride ingress into account, the eyeball survey should be amended to include crack measurements, delamination surveys and cover assessments. The results from this information can be used to measure concrete defects and provide subjective asset condition ratings using the recommended guidelines. Once the weak areas of the concrete structures have been identified, an amended instrument measure method can be adapted for further tests on site. This consists of obtaining the half-cell potential, resistivity and corrosion rate measurements to indicate the likelihood and strength of chloride-induced corrosion activity. Thereafter, concrete cores can be extracted for further deterioration assessment and to predict the remaining service life of the waterside infrastructure using chloride profiling. This will assist TNPA with identifying critical assets, which will inform resource allocation and scheduling of maintenance activities. In addition, the instrument measurement method should be prescribed for the condition assessment of all waterside infrastructure and regarded as a follow-up method to the

eyeball inspection method. Furthermore, in addition to assessing the integrity and scour protection for seawalls, quays and other berthing structures, the diving inspection should include the deterioration assessment of all the inaccessible concrete structures in the tidal, splash spray and submerged zones adhering to the guidelines of the amended eyeball inspection and instrument measure methods. The aerial survey, performed by CSIR, can be used to continue assessing the alignment of the overall breakwater armour protection. However, the deterioration of the concrete breakwater units should be assessed using the amended eyeball inspection and instrument measure methods. A revised frequency of how often these condition assessment methods can be done is also provided to assist with minimising resource constraints experienced by TNPA.

Technology can be utilised to improve asset maintenance as demonstrated by international ports. TNPA currently uses CMMS software such as the SAP PM software to track and manage maintenance activities. Its key functions include creating maintenance plans, adjusting maintenance schedules, loading inspection frequencies and comparing the monthly cashflow with the approved budget. The overall condition of assets in each port can be stored and displayed to track the condition over time. Although these activities are crucial for managing asset maintenance for TNPA, they are heavily dependent on manual entries and do not autonomously make maintenance decisions such as indicating the deteriorating areas of structures, predicting when maintenance is required and predicting their remaining service life. This also limits SAP PM's capability to provide input into TNPA's maintenance strategy. International ports are mitigating these limitations by using smart maintenance technology such as DT technology. The smartBRIDGE Hamburg pilot project in Germany uses a DT model to provide condition indicators of the bridge's components by placing sensors that can detect the deterioration of the concrete structure in its critical locations. This information can be shared with various stakeholders using 3D models and make it easier to interpret the results. Research by Heng et. al. (2023) shows that DT models can also be tailored to assess the deterioration in the marine environment and provide the remaining service life of assets. Furthermore, the DT model developed for the maintenance of pavements in Norvic Port in Sweden shows that the results obtained from analysing DT models can provide insights into improving maintenance strategies and port operations using scenario analyses. Therefore, to address RQ3, smart technology such as DT technology can assist TNPA with independently determining the locations where waterside infrastructure is deteriorating, indicating when maintenance will be required, predicting the remaining service life, optimising maintenance strategies and improving port operations. The gap analysis in Chapter 5 concluded that for TNPA to implement DT technology, the main implementation steps required for the

functioning of DT models would be to install sensors that can detect the deterioration of concrete structures in the marine environment and implement BIM software for 3D modelling capabilities. Key challenges such as high implementation costs, data security risks and the lack of standards and frameworks to guide DT technology implementation should also be taken into consideration when considering implementing DT technology. In the meantime, to fully capitalise on the current technology used in TNPA, inputs into the SAP PM software regarding the frequency of condition assessments and resources required can be modified to include the recommendations provided. The RUL used for the FAR can be informed by the recommended assessment of chloride profiling and service life prediction models.

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## 8 ANNEXURES

### Annexure A: Extract of the Port of Cape Town's 2022 Asset Condition Rating Spreadsheet

|                        |                                   | ASSET CONDITION SUMMARY RATING<br>PORT OF CAPE TOWN OCTOBER 2022 |  |  |  |        |  |  |  |  |  |  |  |                  |
|------------------------|-----------------------------------|--|--|--|--|--------|--|--|--|--|--|--|--|------------------|
| ASSET TYPE AND ELEMENT |                                   | TARGET<br>CONDITION<br>(%)                                       | ACTUAL<br>ASSESSED<br>CONDITION<br>RATING (%)<br>2020/21 | ACTUAL<br>ASSESSED<br>CONDITION<br>RATING (%)<br>2021/22 | ACTUAL<br>ASSESSED<br>CONDITION<br>RATING (%)<br>2022/23 | WEIGHT | WEIGHTED<br>ACTUAL<br>CONDITION<br>RATING<br>2020/21 | WEIGHTED<br>ACTUAL<br>CONDITION<br>RATING<br>2021/22 | WEIGHTED<br>ACTUAL<br>CONDITION<br>RATING<br>2022/23 | Factor<br>(Actual<br>Rating/<br>Target<br>Rating)<br>2019/20 | Factor<br>(Actual<br>Rating/<br>Target<br>Rating)<br>2020/21 | Factor<br>(Actual<br>Rating/<br>Target<br>Rating)<br>2021/22 | Factor<br>(Actual<br>Rating/<br>Target<br>Rating)<br>2022/23 | Reasons/Comments |
| <b>1. CIVIL</b>        |                                   |  |  |  |  |        |  |  |  |  |  |  |  |                  |
| 1.3.                   | Quays & Other Berthing Structures | 10%  |  |  |  |        |  |  |  |  |  |  |  |                  |
| 1.3.1.                 | Quay walls                        | 50%  |  |  |  |        |  |  |  |  |  |  |  |                  |
|                        | Walls, piles                      | 80%  | 0  | 74   | 73   | 30%    | 0.000  | 0.884  | 0.876  | 0.92   | 0.00   | 92%  | 91%  |                  |
|                        | Cope, deck                        | 80%  | 0  | 73   | 78   | 20%    | 0.000  | 0.587  | 0.624  | 0.93   | 0.00   | 92%  | 98%  |                  |
|                        | Toe, scour protection             | 80%  | 0  | 78   | 81   | 15%    | 0.000  | 0.468  | 0.486  | 0.97   | 0.00   | 97%  | 101%   |                  |
|                        | Bollards                          | 80%  | 0  | 81   | 79   | 8%     | 0.000  | 0.259  | 0.253  | 1.03   | 0.00   | 101%   | 99%  |                  |
|                        | Fenders and chains                | 80%  | 0  | 79   | 81   | 10%    | 0.000  | 0.317  | 0.324  | 0.99   | 0.00   | 99%  | 101%   |                  |
|                        | Ladders                           | 80%  | 0  | 81   | 95   | 2%     | 0.000  | 0.065  | 0.076  | 1.01   | 0.00   | 101%   | 119%   |                  |
|                        | Services tunnel                   | 80%  | 0  | 95   | 79   | 10%    | 0.000  | 0.379  | 0.316  | 1.18   | 0.00   | 118%   | 99%  |                  |
|                        | Services                          | 80%  | 0  | 79   | 79   | 5%     | 0.000  | 0.158  | 0.158  | 0.99   | 0.00   | 99%  | 99%  |                  |
| 1.3.2.                 | Jetties                           | 25%  |  |  |  |        |  |  |  |  |  |  |  |                  |
|                        | Deck                              | 90%  |  |  | 75   | 25%    | 0.000  | 0.000  | 0.422  | 0.00   | 0.00   | 0.00   | 83%  |                  |
|                        | Pile structure                    | 90%  |  |  | 62   | 25%    | 0.000  | 0.000  | 0.349  | 0.00   | 0.00   | 0.00   | 69%  |                  |
|                        | Scour protection                  | 90%  |  |  | 95   | 15%    | 0.000  | 0.000  | 0.321  | 0.00   | 0.00   | 0.00   | 106%   |                  |
|                        | Hand rails                        | 90%  |  |  | 90   | 10%    | 0.000  | 0.000  | 0.203  | 0.00   | 0.00   | 0.00   | 100%   |                  |
|                        | Bollards                          | 90%  |  |  | 85   | 8%     | 0.000  | 0.000  | 0.153  | 0.00   | 0.00   | 0.00   | 94%  |                  |
|                        | Fenders and chains                | 90%  |  |  | 60   | 10%    | 0.000  | 0.000  | 0.135  | 0.00   | 0.00   | 0.00   | 67%  |                  |
|                        | Ladders                           | 90%  |  |  | 70   | 2%     | 0.000  | 0.000  | 0.032  | 0.00   | 0.00   | 0.00   | 78%  |                  |
|                        | Services                          | 90%  |  |  | 80   | 5%     | 0.000  | 0.000  | 0.090  | 0.00   | 0.00   | 0.00   | 89%  |                  |
| 1.3.3.                 | Dolphins                          | 25%  |  |  |  |        |  |  |  |  |  |  |  |                  |
|                        | Deck, caisson, blockwork          | 80%  | 0  | 72   | 72   | 15%    | 0.000  | 1.620  | 0.217  | 0.94   | 0.00   | 90%  | 90%  |                  |
|                        | Pile structure                    | 80%  | 0  | 73   | 73   | 20%    | 0.000  | 2.190  | 0.292  | 0.94   | 0.00   | 91%  | 91%  |                  |
|                        | Scour protection                  | 80%  | 0  | 69   | 69   | 10%    | 0.000  | 1.035  | 0.138  | 0.89   | 0.00   | 86%  | 86%  |                  |

## Annexure B: Asset Condition Ratings for all Ports Between 2017 and 2022

| PORT                  | ACTUAL ASSET CONDITION RATINGS |         |         |         |         |         |
|-----------------------|--------------------------------|---------|---------|---------|---------|---------|
|                       | 2017/18                        | 2018/19 | 2019/20 | 2020/21 | 2021/22 | Average |
| <b>Saldana</b>        | 77.29%                         | 78.64%  | 78.99%  | 79.57%  | 79.57%  | 78.81%  |
| <b>Cape Town</b>      | 67.19%                         | 68.38%  | 69.07%  | 69.07%  | 69.07%  | 68.56%  |
| <b>Mosel Bay</b>      | 60.28%                         | 64.00%  | 64.10%  | 63.90%  | 65.90%  | 63.64%  |
| <b>Port Elizabeth</b> | 80.00%                         | 80.00%  | 79.00%  | 79.60%  | 79.60%  | 79.64%  |
| <b>Ngqura</b>         | 79.25%                         | 78.21%  | 77.80%  | 76.71%  | 77.35%  | 77.86%  |
| <b>East London</b>    | 80.90%                         | 80.89%  | 81.71%  | 80.09%  | 80.90%  | 80.90%  |
| <b>Durban</b>         | 82.81%                         | 84.54%  | 82.59%  | 86.37%  | 85.19%  | 84.30%  |
| <b>Richards Bay</b>   | 72.35%                         | 71.61%  | 70.84%  | 71.65%  | 71.81%  | 71.65%  |
| <b>Average</b>        | 75.01%                         | 75.78%  | 75.51%  | 75.87%  | 76.17%  |         |

## Annexure C: Historical condition assessment results for all structures (2020 to 2023)

### Annexure C1: Port of Cape Town condition assessments for breakwaters

| Year | AMPP Maintenance Method | Item inspected       | Comments and/or Recommendations for Follow-Up Assessments |  |
|------|-------------------------|----------------------|---|--|
| 2020 | Eyeball Method          | Main breakwater      | Overall Armour  | Recommendation to conduct aerial survey and damage assessment annually.  |
|      |                         |                      | Spur  | Spur recently restored in 2018; no further work required.  |
|      |                         |                      | Trunk   | Recommendation to repair damaged capping.  |
|      |                         |                      | Caissons  | Recommendations: <ul style="list-style-type: none"> <li>• Further conduct diving assessment for scour movement.</li> <li>• Develop concrete repair specification</li> <li>• Conduct minor concrete repairs</li> </ul>  |
|      |                         | Secondary breakwater | Eastern Mole  | Recommendations: <ul style="list-style-type: none"> <li>• Place units correctly using mobile crane</li> <li>• Develop concrete repair specification</li> <li>• Assessment required to determine if repair is required, based on possible redesign</li> </ul> |

|             |                      |                 |  |  |
|-------------|----------------------|-----------------|--|--|
|             |                      |                 | A-Berth  | Coastal protection intervention recommended for the erosion              |
| <b>2021</b> | Eyeball Method       | Main breakwater | Overall  | Recommendation to conduct aerial survey and damage assessment annually.  |
|             |                      |                 | Armour   |  |
|             |                      |                 | Spur   | Spur recently restored in 2018; no further work required.                |
|             |                      |                 | Trunk  | Recommendation to repair damaged capping. More damage has been observed. |
|             |                      | Caissons        | Recommendations: <ul style="list-style-type: none"> <li>• Develop concrete repair specification</li> <li>• Conduct minor concrete repairs</li> </ul>   |  |
|             | Secondary breakwater | Eastern Mole    | Recommendations: <ul style="list-style-type: none"> <li>• Place units correctly using mobile crane</li> <li>• Develop concrete repair specification</li> <li>• Assessment required to determine if repair is required, based on possible redesign</li> </ul> |  |
|             |                      |                 | A-Berth  | Coastal protection intervention recommended for the erosion              |
|             | Diving Inspection    | Main Breakwater | Caisson  | Diving inspection results for scour movement not yet assessed.           |
| <b>2022</b> | Eyeball Method       | Main breakwater | Overall  | Recommendation to conduct aerial survey and damage assessment annually.  |
|             |                      |                 | Armour   |  |
|             |                      |                 | Spur   | Spur recently restored in 2018; no further work required.                |
|             |                      |                 | Trunk  | Recommendation to repair damaged capping. More damage observed.          |
|             |                      |                 | Caissons   | Recommendations:   |

|             |                |                      |                |  |
|-------------|----------------|----------------------|----------------|--|
|             |                |                      |                | <ul style="list-style-type: none"> <li>Assess 2021 diving assessment result for scour movement.</li> <li>Develop concrete repair specification</li> <li>Conduct minor concrete repairs</li> </ul>  |
|             |                | Secondary breakwater | Eastern Mole   | Recommendations: <ul style="list-style-type: none"> <li>Place units correctly using mobile crane</li> <li>Develop concrete repair specification</li> <li>Assessment required to determine if repair is required, based on possible redesign</li> </ul> |
|             |                |                      | A-Berth        | Coastal protection intervention recommended for the erosion  |
| <b>2023</b> | Eyeball Method | Main breakwater      | Overall Armour | Recommendation to conduct aerial survey and damage assessment annually.  |
|             |                |                      | Spur           | Spur recently restored in 2018; no further work required.  |
|             |                |                      | Trunk          | Recommendation to repair damaged capping. More damage observed.  |
|             |                |                      | Caissons       | Recommendations: <ul style="list-style-type: none"> <li>Assess 2021 diving assessment result for scour movement.</li> <li>Develop concrete repair specification</li> </ul> Conduct minor concrete repairs  |
|             |                | Secondary breakwater | Eastern Mole   | Recommendations: <ul style="list-style-type: none"> <li>Place units correctly using mobile crane</li> <li>Develop concrete repair specification</li> <li>Assessment required to determine if repair is required, based on possible redesign</li> </ul> |

|  |  |  |         |   |
|--|--|--|---------|---|
|  |  |  | A-Berth | Coastal protection intervention recommended for the erosion |
|--|--|--|---------|---|

### Annexure C2: Historical condition assessments for dry docks

| Year | AMPP Maintenance Method | Item inspected   | Comments/<br>Follow-Up Assessments             | Port structure   |
|------|-------------------------|------------------|--|--|
| 2020 | Eyeball Method          | Sturrock Drydock | Main Graving Dock – overall concrete structure | Severe concrete spalling should be addressed urgently. Repairs should be included in upcoming capital project.   |
|      |                         |                  | Graving dock paving                            | Heavy trucks have severely damaged the concrete and gravel pavement. Repairs should be addressed in upcoming capital project.                                    |
|      |                         | Syncrolift       | Repair bays                                    | Damaged and neglected. Repairs should be addressed in upcoming capital project.  |
|      |                         |                  | Syncrolift structure                           | Severe concrete scaling requires urgent attention. Capital project recommended to repair damage based on the damage extent.                                      |
| 2021 | Eyeball Method          | Sturrock Drydock | Main Graving Dock –                            | <ul style="list-style-type: none"> <li>Severe concrete spalling should be addressed urgently. Repairs should be included in upcoming capital project.</li> </ul> |

|             |                                    |   |                                       |   |
|-------------|------------------------------------|---|---------------------------------------|---|
|             |                                    |   | overall concrete structure            | <ul style="list-style-type: none"> <li>• Recommendation for yearly concrete project to address concrete failure</li> </ul>  |
|             |                                    |   | Graving dock paving                   | Heavy trucks have severely damaged the concrete and gravel pavement. Repairs should be addressed in upcoming capital project (same comment as previous year)                                  |
|             |                                    | Syncrolift  | Repair bays                           | <ul style="list-style-type: none"> <li>• Damaged and neglected. Repairs should be addressed in upcoming capital project.</li> <li>• Concrete slabs cut to address drainage problem</li> </ul> |
|             |                                    |   | Syncrolift overall concrete structure | Severe concrete scaling requires urgent attention. Capital project recommended to repair damage based on the damage extent (same comment as previous year).                                   |
| <b>2022</b> | No condition assessments conducted |   |                                       |   |
| <b>2023</b> | Eyeball Method                     | Only mechanical equipment inspected. No assessment for concrete structures. |                                       |   |

### Annexure C3: Historical condition assessments for quays and berthing structures

| Year | AMPP Maintenance Method             | Item inspected           | Comments/<br>Follow-Up Assessments  |
|------|-------------------------------------|--------------------------|---|
| 2020 | No condition assessments conducted. |                          |   |
| 2021 | Eyeball Method                      | A-Berths                 | <ul style="list-style-type: none"> <li>Removal and replacement of steel concrete tower that was knocked down.</li> <li>Detailed condition assessment required for service tunnel due to large concrete cracks and spalling of concrete patches observed.</li> </ul> |
|      |                                     | B-D Berths               | <ul style="list-style-type: none"> <li>Detailed condition assessment required for concrete cracks and spalling observed.</li> </ul>   |
|      |                                     | E-L Berths               | <ul style="list-style-type: none"> <li>Isolated patches of spalling observed.</li> </ul>  |
|      |                                     | Globe Quay               | <ul style="list-style-type: none"> <li>Intervention required for severely corroded sheet pile quay wall.</li> </ul>   |
|      |                                     | Tanker Basin Cross Berth | <ul style="list-style-type: none"> <li>Detailed condition assessment required for severely corroded sheet pile wall. Holes observed, which could allow leaching of fines.</li> </ul>  |
|      |                                     | Hamlet Quay              | <ul style="list-style-type: none"> <li>Detailed condition assessment required for severely corroded sheet pile wall. Holes observed, which could allow leaching of fines</li> </ul>   |
|      |                                     | Outeniqua Quay           | <ul style="list-style-type: none"> <li>Diving inspection required to assess concrete structure behind fenders.</li> </ul>   |
|      |                                     | South-East Counterfort   | <ul style="list-style-type: none"> <li>Removal of unwanted pillars on the seabed required.</li> </ul>   |
|      |                                     | Springbok Quay           | <ul style="list-style-type: none"> <li>Diving inspection required</li> </ul>  |

|      |                |               |   |
|------|----------------|---------------|---|
|      |                |               | <ul style="list-style-type: none"> <li>Detailed condition assessment required for longitudinal concrete crack on the splash wall caused by a vessel.</li> </ul>   |
|      |                | Berth 500     | <ul style="list-style-type: none"> <li>Longitudinal concrete crack observed and should be monitored.</li> <li>Damaged concrete capping should be repaired</li> </ul>  |
|      |                | Quays 501-502 | <ul style="list-style-type: none"> <li>Longitudinal concrete cracked observed and should be monitored.</li> <li>Diving inspection required.</li> </ul>  |
|      |                | Quays 600-601 | <ul style="list-style-type: none"> <li>Longitudinal concrete cracking observed and should be monitored.</li> </ul>  |
|      |                | Quay 700      | <ul style="list-style-type: none"> <li>Longitudinal concrete cracking observed and should be monitored</li> </ul>   |
|      |                | Quays 701-702 | <ul style="list-style-type: none"> <li>Longitudinal cracking, steel corrosion and damaged concrete capping observed.</li> <li>Detailed condition assessment required for cause and repair.</li> </ul>   |
|      |                | Berth 703     | <ul style="list-style-type: none"> <li>Leaching and rust stains observed on the wall.</li> <li>Recommendation to monitor deterioration.</li> </ul>  |
|      |                | Berth 704     | <ul style="list-style-type: none"> <li>Severe cracking observed on the edge of the surface.</li> <li>Recommendation to monitor deterioration.</li> </ul>  |
|      |                | Jetty 1       | <ul style="list-style-type: none"> <li>Severe cracking observed on the edge of the surface</li> <li>Recommendation to monitor deterioration.</li> </ul>   |
| 2022 | Eyeball Method | A-Berths      | <ul style="list-style-type: none"> <li>Removal and replacement of steel concrete tower that was knocked down.</li> <li>Detailed condition assessment required for service tunnel due to large concrete cracks and spalling of concrete patches observed.</li> </ul> |
|      |                | B-D Berths    | <ul style="list-style-type: none"> <li>Detailed condition assessment required for concrete cracks and spalling observed.</li> </ul>   |

|  |                          |  |
|--|--------------------------|--|
|  | E-L Berths               | <ul style="list-style-type: none"> <li>Isolated patches of spalling observed.</li> </ul>   |
|  | Globe Quay               | <ul style="list-style-type: none"> <li>Intervention required for severely corroded sheet pile quay wall.</li> </ul>  |
|  | Tanker Basin Cross Berth | <ul style="list-style-type: none"> <li>Detailed condition assessment required for severely corroded sheet pile wall. Holes observed, which could allow leaching of fines.</li> </ul>                 |
|  | Hamlet Quay              | <ul style="list-style-type: none"> <li>Detailed condition assessment required for severely corroded sheet pile wall. Holes observed, which could allow leaching of fines</li> </ul>                  |
|  | Outeniqua Quay           | <ul style="list-style-type: none"> <li>Diving inspection required to assess concrete structure behind fenders.</li> </ul>  |
|  | South-East Counterfort   | <ul style="list-style-type: none"> <li>Removal of unwanted pillars on the seabed required.</li> </ul>  |
|  | Springbok Quay           | <ul style="list-style-type: none"> <li>Diving inspection required</li> <li>Detailed condition assessment required for longitudinal concrete crack on the splash wall caused by a vessel.</li> </ul>  |
|  | Berth 500                | <ul style="list-style-type: none"> <li>Longitudinal concrete crack observed and should be monitored.</li> <li>Damaged concrete capping should be repaired</li> </ul>                                 |
|  | Quays 501-502            | <ul style="list-style-type: none"> <li>Longitudinal concrete cracks observed and should be monitored.</li> <li>Diving inspection required.</li> </ul>  |
|  | Quays 600-601            | <ul style="list-style-type: none"> <li>Longitudinal concrete cracking observed and should be monitored.</li> </ul>   |
|  | Quay 700                 | <ul style="list-style-type: none"> <li>Longitudinal concrete cracking observed and should be monitored</li> </ul>  |
|  | Quays 701-702            | <ul style="list-style-type: none"> <li>Longitudinal cracking, steel corrosion and damaged concrete capping observed.</li> <li>Detailed condition assessment required for cause and repair</li> </ul> |

|      |                |                             |  |
|------|----------------|-----------------------------|--|
|      |                | Berth 703                   | <ul style="list-style-type: none"> <li>Leaching and rust stains observed on the wall.</li> <li>Recommendation to monitor deterioration.</li> </ul>   |
|      |                | Berth 704                   | <ul style="list-style-type: none"> <li>Severe cracking observed on the edge of the surface.</li> <li>Recommendation to monitor deterioration.</li> </ul>   |
|      |                | Jetty 1                     | <ul style="list-style-type: none"> <li>Severe cracking observed on the edge of the surface</li> <li>No recommendations provided.</li> </ul>  |
| 2023 | Eyeball Method | Tanker Basin 1              | <ul style="list-style-type: none"> <li>Detailed condition assessment required to assess the condition of the piles below water level.</li> </ul>   |
|      |                | Tanker Basin 2              | <ul style="list-style-type: none"> <li>Urgent action required to address the corroding post-tensioning steel on catwalk which has been exposed due to concrete damage caused by a vessel.</li> <li>Detailed condition assessment required to assess the condition of the piles below water level.</li> </ul> |
|      |                | Eastern Mole Re-routed      | <ul style="list-style-type: none"> <li>Concrete spalling, exposed reinforcing steel and eroding scour protection observed.</li> <li>Recommendation to monitor the deterioration.</li> </ul>  |
|      |                | Eastern Mole                | <ul style="list-style-type: none"> <li>Rust staining and cracking observed on the edge of the surface.</li> <li>Recommendation to monitor the deterioration</li> </ul>   |
|      |                | Eastern Mole Berths 1 and 2 | <ul style="list-style-type: none"> <li>Severe concrete spalling, cracking and exposed reinforcing steel observed.</li> <li>Recommendation to install rubber sleeves on fender to prevent further damage.</li> </ul>  |

### Annexure C4: Historical condition assessments for seawalls

| Year        | AMPP Maintenance Method             | Item inspected            | Comments/<br>Follow-Up Assessments  |
|-------------|-------------------------------------|---------------------------|---|
| <b>2020</b> | No condition assessments conducted. |                           |   |
| <b>2021</b> | Eyeball Method                      | Sewall at BSD             | No major deterioration observed, condition of the structure must be monitored using a multibeam and laser scanner. Divers required to assess condition of the toe.        |
|             |                                     | Revetment at A-Berth      | Excessive erosion observed. In some sections, the revetment is no longer maintaining its function of protecting against wave action or surges. Urgent repair is required. |
|             |                                     | Revetment at Eastern Mole | Multibeam and laser scan assessments to determine if there is any deterioration on the slope. An aerial condition assessment is also required.                            |
| <b>2022</b> | Eyeball Method                      | Sewall on BSD             | No major deterioration observed, condition of the structure must be monitored using a multibeam and laser scanner. Divers required to assess condition of the toe.        |
|             |                                     | Revetment at A-Berth      | Excessive erosion observed. In some sections, the revetment is no longer maintaining its function of protecting against wave action or surges. Urgent repair is required. |
|             |                                     | Sewall on BSD             | No major deterioration observed, condition of the structure must be monitored using a multibeam and laser scanner. Divers required to assess condition of the toe.        |
| <b>2023</b> | Eyeball Method                      | Sewall on BSD             | No major deterioration observed, condition of the structure must be monitored using a multibeam and laser scanner. Divers required to assess condition of the toe.        |
|             |                                     | Revetment at A-Berth      | Excessive erosion observed. In some sections, the revetment is no longer maintaining its function of protecting against wave action or surges. Urgent repair is required. |

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|  |  |                  |  |
|--|--|------------------|--|
|  |  | Sewall on<br>BSD | No major deterioration observed, condition of the structure must be monitored using a multibeam and laser scanner. Divers required to assess condition of the toe. |
|--|--|------------------|--|

## Annexure D: Waterside Asset Condition Ratings

### Annexure D1: Asset Condition Ratings for Breakwaters

| Item                | Minimum Target | Weighting   | Actual Asset Condition Ratings |         |            | Weighted Actual Condition Ratings |            |            |
|---------------------|----------------|-------------|--------------------------------|---------|------------|-----------------------------------|------------|------------|
|                     |                |             | 2020/21                        | 2021/22 | 2022/23    | 2020/21                           | 2021/22    | 2022/23    |
| <b>Armour Outer</b> | 85%            | 55%         | 60%                            | 60%     | 59%        | 33%                               | 33%        | 32%        |
| Armour inner        | 85%            | 10%         | 60%                            | 60%     | 59%        | 6%                                | 6%         | 6%         |
| Toe - outer         | 85%            | 8%          | 64%                            | 64%     | 63%        | 5%                                | 5%         | 5%         |
| Toe - inner         | 85%            | 5%          | 66%                            | 66%     | 65%        | 3%                                | 3%         | 3%         |
| Splash Wall         | 85%            | 10%         | 69%                            | 69%     | 68%        | 7%                                | 7%         | 7%         |
| Top structure       | 70%            | 10%         | 55%                            | 55%     | 55%        | 6%                                | 6%         | 6%         |
| Services            | 70%            | 2%          | 76%                            | 76%     | 75%        | 2%                                | 2%         | 2%         |
|                     | <b>83%</b>     | <b>100%</b> |                                |         | <b>Sum</b> | <b>61%</b>                        | <b>61%</b> | <b>60%</b> |

### Annexure D2: Asset Condition Ratings for Drydocks

| Item         | Minimum Target | Weighting | Actual Asset Condition Ratings |         |         | Weighted Actual Condition Ratings |         |         |
|--------------|----------------|-----------|--------------------------------|---------|---------|-----------------------------------|---------|---------|
|              |                |           | 2020/21                        | 2021/22 | 2022/23 | 2020/21                           | 2021/22 | 2022/23 |
| <b>Walls</b> | 90%            | 15%       | 53%                            | 53%     | 53%     | 8%                                | 8%      | 8%      |
| Gates        | 90%            | 15%       | 35%                            | 35%     | 35%     | 5%                                | 5%      | 5%      |

|                                |            |             |     |     |            |            |            |            |
|--------------------------------|------------|-------------|-----|-----|------------|------------|------------|------------|
| Grooves                        | 90%        | 10%         | 0%  | 0%  | 0%         | 0%         | 0%         | 0%         |
| Steps, landings, ledges        | 90%        | 10%         | 55% | 60% | 60%        | 6%         | 6%         | 6%         |
| Tunnels, conduits              | 90%        | 5%          | 53% | 63% | 63%        | 3%         | 3%         | 3%         |
| Fenders                        | 90%        | 5%          | 68% | 68% | 68%        | 3%         | 3%         | 3%         |
| Crane rails                    | 90%        | 10%         | 70% | 65% | 65%        | 7%         | 7%         | 7%         |
| Hydrants                       | 90%        | 5%          | 70% | 53% | 68%        | 4%         | 3%         | 3%         |
| Markings                       | 90%        | 5%          | 48% | 43% | 65%        | 2%         | 2%         | 3%         |
| Hatches, manholes, crane boxes | 90%        | 5%          | 30% | 30% | 63%        | 2%         | 2%         | 3%         |
| Handrails, escape-ladders      | 90%        | 10%         | 45% | 45% | 45%        | 5%         | 5%         | 5%         |
| Flood & emergency valves       | 90%        | 5%          | 43% | 43% | 43%        | 2%         | 2%         | 2%         |
|                                | <b>90%</b> | <b>100%</b> |     |     | <b>Sum</b> | <b>46%</b> | <b>45%</b> | <b>49%</b> |

### Annexure D3: Asset Condition Ratings for Quays & Other Berthing Structures

| Item                    | Minimum Target | Weighting | Actual Asset Condition Ratings |         |         | Weighted Actual Condition Ratings |         |         |
|-------------------------|----------------|-----------|--------------------------------|---------|---------|-----------------------------------|---------|---------|
|                         |                |           | 2020/21                        | 2021/22 | 2022/23 | 2020/21                           | 2021/22 | 2022/23 |
| <b>Quay walls (50%)</b> |                |           |                                |         |         |                                   |         |         |
| <b>Walls, piles</b>     | 80%            | 30%       | 0%                             | 74%     | 73%     | 0%                                | 22%     | 22%     |
| Cope, deck              | 80%            | 20%       | 0%                             | 73%     | 78%     | 0%                                | 15%     | 16%     |
| Toe, scour protection   | 80%            | 15%       | 0%                             | 78%     | 81%     | 0%                                | 12%     | 12%     |

|                                 |            |             |    |     |            |           |            |            |
|---------------------------------|------------|-------------|----|-----|------------|-----------|------------|------------|
| Bollards                        | 80%        | 8%          | 0% | 81% | 79%        | 0%        | 6%         | 6%         |
| Fenders and chains              | 80%        | 10%         | 0% | 79% | 81%        | 0%        | 8%         | 8%         |
| Ladders                         | 80%        | 2%          | 0% | 81% | 95%        | 0%        | 2%         | 2%         |
| Services tunnel                 | 80%        | 10%         | 0% | 95% | 79%        | 0%        | 9%         | 8%         |
| Services                        | 80%        | 5%          | 0% | 79% | 79%        | 0%        | 4%         | 4%         |
|                                 | <b>80%</b> | <b>100%</b> |    |     | <b>Sum</b> | <b>0%</b> | <b>78%</b> | <b>78%</b> |
| <b>Jetties (25%)</b>            |            |             |    |     |            |           |            |            |
| <b>Deck</b>                     | 90%        | 25%         | 0% | 0%  | 75%        | 0%        | 19%        | 19%        |
| Pile structure                  | 90%        | 25%         | 0% | 0%  | 62%        | 0%        | 16%        | 16%        |
| Scour protection                | 90%        | 15%         | 0% | 0%  | 95%        | 0%        | 14%        | 14%        |
| Hand rails                      | 90%        | 10%         | 0% | 0%  | 90%        | 0%        | 9%         | 9%         |
| Bollards                        | 90%        | 8%          | 0% | 0%  | 85%        | 0%        | 7%         | 7%         |
| Fenders and chains              | 90%        | 10%         | 0% | 0%  | 60%        | 0%        | 6%         | 6%         |
| Ladders                         | 90%        | 2%          | 0% | 0%  | 70%        | 0%        | 1%         | 1%         |
| Services                        | 90%        | 5%          | 0% | 0%  | 80%        | 0%        | 4%         | 4%         |
|                                 | <b>90%</b> | <b>100%</b> |    |     | <b>Sum</b> | <b>0%</b> | <b>76%</b> | <b>76%</b> |
| <b>Dolphins (25%)</b>           |            |             |    |     |            |           |            |            |
| <b>Deck, caisson, blockwork</b> | 80%        | 15%         | 0% | 72% | 72%        | 0%        | 11%        | 11%        |
| Pile structure                  | 80%        | 20%         | 0% | 73% | 73%        | 0%        | 15%        | 15%        |
| Scour protection                | 80%        | 10%         | 0% | 69% | 69%        | 0%        | 7%         | 7%         |
| Hand rails                      | 80%        | 10%         | 0% | 61% | 61%        | 0%        | 6%         | 6%         |

|                    |            |             |    |                     |            |           |            |            |
|--------------------|------------|-------------|----|---------------------|------------|-----------|------------|------------|
| Bollards           | 80%        | 8%          | 0% | 70%                 | 70%        | 0%        | 6%         | 6%         |
| Fenders and chains | 80%        | 10%         | 0% | 72%                 | 72%        | 0%        | 7%         | 7%         |
| Ladders            | 80%        | 2%          | 0% | 64%                 | 64%        | 0%        | 1%         | 1%         |
| Services           | 80%        | 5%          | 0% | 69%                 | 69%        | 0%        | 3%         | 3%         |
| Approach bridge    | 80%        | 10%         | 0% | 80%                 | 80%        | 0%        | 8%         | 8%         |
| Catwalk            | 80%        | 10%         | 0% | 60%                 | 60%        | 0%        | 6%         | 6%         |
|                    | <b>80%</b> | <b>100%</b> |    |                     | <b>Sum</b> | <b>0%</b> | <b>70%</b> | <b>70%</b> |
|                    | <b>83%</b> |             |    | <b>Weighted Sum</b> |            | <b>0%</b> | <b>38%</b> | <b>75%</b> |

#### Annexure D4: Asset Condition Ratings for Seawalls

| Item                     | Minimum Target | Weighting   | Actual Asset Condition Ratings |         |            | Weighted Actual Condition Ratings |            |            |
|--------------------------|----------------|-------------|--------------------------------|---------|------------|-----------------------------------|------------|------------|
|                          |                |             | 2020/21                        | 2021/22 | 2022/23    | 2020/21                           | 2021/22    | 2022/23    |
| <b>Armour protection</b> | 80%            | 45%         | 0%                             | 66%     | 66%        | 0%                                | 30%        | 30%        |
| Toe                      | 80%            | 20%         | 0%                             | 68%     | 68%        | 0%                                | 14%        | 14%        |
| Backup area              | 80%            | 15%         | 0%                             | 69%     | 69%        | 0%                                | 10%        | 10%        |
| Services                 | 80%            | 10%         | 0%                             | 76%     | 76%        | 0%                                | 8%         | 8%         |
| Splash wall              | 85%            | 10%         | 0%                             | 0%      | 0%         | 0%                                | 0%         | 0%         |
|                          | <b>81%</b>     | <b>100%</b> |                                |         | <b>Sum</b> | <b>0%</b>                         | <b>61%</b> | <b>61%</b> |