

COMPARISON and EVALUATION
of SOUTH AFRICAN POLETOP DESIGNS for
11kV and 22kV RURAL DISTRIBUTION LINES

Prepared by: R. A. Scott Pr.Eng., B.Sc.(Physics), B.Sc.(Elec. Eng.)

Prepared for: The Department of Electrical and Electronic Engineering
UNIVERSITY of CAPE TOWN

March 1992

Thesis prepared in fulfilment of requirements for the degree of MSc in Electrical and Electronic Engineering.

The University of Cape Town has been given
the right to reproduce this thesis in whole
or in part. Copyright is held by the author.

The copyright of this thesis vests in the author. No quotation from it or information derived from it is to be published without full acknowledgement of the source. The thesis is to be used for private study or non-commercial research purposes only.

Published by the University of Cape Town (UCT) in terms of the non-exclusive license granted to UCT by the author.

ACKNOWLEDGEMENTS

The writer wishes to thank:

All his colleagues throughout Eskom who provided drawings and information,

The librarians at Eskom and UCT who searched for and found much needed articles and publications,

His thesis supervisor, Charles Dingley, for his valued criticism and encouragement,

and Eskom Western Cape Regional Management, who authorised and provided study aid assistance and facilities for this research.

The writer prepared all text and illustrations and took all the photographs, except those specifically acknowledged.

CONTENTS

Chapter	Page
1 Introduction to the thesis	1
1.1 Background and rationale	2
1.2 Research on which this thesis is based	5
1.3 A guide to the thesis	7
2 Poletop configuration designs used in practice	9
2.1 South African practice	10
2.2 Representative overseas designs	24
3 An evaluation of line design theory	33
3.1 An assessment of the literature surveyed	35
3.2 A simplified design procedure for a rural line	37
3.3 Design of the line with respect to spans, sags and tensions	40
3.3.1 Design parameters for South African conditions	
3.3.2 Basic formulae for the calculation of sag	
3.3.3 Calculation of conductor sags and tensions for different conditions	
3.4 Resistance of intermediate poles to bending forces caused by wind load on the conductors and structure	48
3.4.1 Wind load calculations: South African Code of Practice	
3.4.2 Wind load calculations: Rural Electrification Administration, USA	
3.4.3 Comparison of factors applicable to the calculations	
3.4.4 Calculation of the safe bending load for a pole	
3.4.5 Pole testing stress, permissible stress and rupture stress	
3.5 Pole foundations	63
3.5.1 The properties of the soil	
3.5.2 Pole foundations: South African Code of Practice	
3.5.3 Morecombe's formulae for soil rupturing intensity	
3.5.4 Pole foundations: Australian guidelines	
3.5.5 Current Practice in the United States of America	

3.5.6	The effect of backfill quality on foundations	
3.5.7	Stein's unified formula for pole foundations	
3.5.8	Comparisons of the formulae for pole foundations	
3.6	The spacing of the conductors at the crossarm structure	84
3.6.1	An early theory on conductor spacing	
3.6.2	Conductor spacing: South African Code of Practice	
3.6.3	Conductor spacing: Rural Electrification Administration, U.S.A.	
3.6.4	McCombe and Haigh's formula for conductor spacing	
3.6.5	VDE (Germany): horizontal spacing	
3.6.6	Comparisons of formulae for conductor spacing	
3.6.7	Galloping of conductors	
3.7	Precautions to minimise the effect of lightning on rural distribution lines	94
3.7.1	Results of direct lightning strikes	
3.7.2	Results of indirect lightning strikes	
3.7.3	Flashovers and the development of power-frequency arcs	
3.7.4	Impulse withstand level of a structure	
3.7.5	Poletop structure hardware used to limit lightning effects or damage	
3.8	Formulae for the calculation of volt drop and electrical losses	101
3.8.1	An outline of a procedure used for designing the electrical aspects of a rural distribution line	
3.8.2	The thermal operating limit of the line	
3.8.3	Factors influencing the loss parameters	
3.8.4	Comparisons of formulae for the calculation of the volt drop of distribution lines	
3.9	The effect of rural lines on the environment and on wildlife	109
3.9.1	The effect of rural distribution line structures on the ecology	
3.9.2	Prevention of wildlife fatalities	
4	Analysis of South African practice	112
4.1	Details of selected designs	113

4.2	Scope of the analysis	114
4.3	Analysis and comparison of the configurations	116
4.3.1	Sags and clearances	
4.3.2	Stress developed in a pole at ground level	
4.3.3	Resistance of the soil to overturning of the pole	
4.3.4	Conductor spacing and span limitations	
4.3.5	Volt drop along a line	
4.3.6	Environmental hazard	
4.3.7	Comparative estimated costs for the construction of rural lines	
4.3.8	Discussion of the comparative costs of construction of rural lines	
4.4	Examination of the factors limiting the useable span	141
5	Conclusions	146
5.1	Direct results of the research	147
5.2	Indirect results of the research	151
5.3	Further research	154
	References	155

SYMBOLS AND UNITS

It became apparent during the survey of the literature that common symbols and units, on which to base calculations, discussions and comparisons, would have to be used. Also, any formulae used would have to be metricated and only the metric form used in the thesis in order to avoid confusion and unnecessary repetition. Changes that have been made are noted in the text at the appropriate place. Fortunately, it has been possible to specify a set of symbols which are logical in their derivation, which have minimal clashes of use and which are consistent with the main sources of reference. The following two pages list the symbols, their meanings and units. In general, the main symbol specifies the property being measured (eg d for diameter) and the subscript specifies the item being measured (eg d_c for conductor diameter). Unit multiples (eg Kn) or fractions (eg mm) are implied for all units and are defined in the text.

SYMBOL	MEANING	UNITS
A	area	m^2
C	unit capacitance	F/m
E	Young's modulus	N/mm^2
F	force	N
H	horizontal tension	N
I	current	A
L	unit inductance	H/m
L_i	unit internal inductance	H/m
M	moment	Nm
P_w	wind pressure	Pa
R	resistance	ohms
T	conductor tension	N
V	voltage	V
X	reactance	ohms
Z	section modulus	m^3

SYMBOL	MEANING	UNITS
a	angle	degrees
c	conductor spacing (clearance)	m
c _e	equivalent spacing	m
c ₁ etc	individual spacing	m
c _a	arc spacing	m
c _p	phase-to-phase spacing	m
d	diameter	m
d _e	equivalent diameter	m
d _t	pole diameter at top	m
d _g	pole diameter at ground level	m
d _c	conductor diameter	m
e	coefficient of expansion	°C ⁻¹
f _b	bending stress	Pa
h	height above ground level	m
h ₁ etc	individual height	m
k	shape factor	-
k _s	safety factor	-
k _e	"experience" factor	-
k ₁ etc	stress factors	-
l	span	m
l _w	wind span	m
l _m	weight (mass) span	m
p	pole setting depth	m
q	soil load-bearing property	Pa or Pa/m
s	span	m
t	temperature	°C
v _w	wind velocity	km/h
w	unit mass (weight)	N/m
w _c	conductor unit mass (weight)	N/m

CHAPTER 1

INTRODUCTION TO THE THESIS

The ultimate purpose of this thesis is to compare and evaluate South African poletop designs for 11kV and 22kV rural distribution lines. However, a frame of reference is first established from the literature and from construction practice before the analytical stage is tackled.

This introductory chapter is divided into three sections, each covering different aspects of the thesis. The first gives the background and sets out the rationale of the thesis. The next section describes the research on which the thesis is based. The third provides a guide to the thesis, giving broad outlines of the contents of each chapter and section.

1.1 BACKGROUND AND RATIONALE

In 1989, when the work for this thesis was started, it was quite apparent that there existed a proliferation of configuration designs for rural overhead lines at 11kV and 22kV in South Africa.

The electricity supply industry did not use a universal configuration. Eskom supplied over 97% of South Africa's electricity in 1990 (Eskom, 1990). It was also operating 160 280km of lines at 22kV and below in that year and was largely responsible for this situation. Local supply authorities or distributors such as municipalities either bought components from Eskom or used an Eskom design, or developed their own designs internally or via consultants. In any event, the designs they used are not considered to be a significant portion of the total.

Historically, Eskom developed on a strongly regionalised basis, the separate Undertakings joining up (electrically) to form the national grid in 1973. Prior to 1985 there were six Regions distributing the electricity generated by the power stations. Each Region developed its own designs, independently or based on designs imported from Britain.

After 1985 the six Regions were rearranged to become twelve and new configuration designs began to appear. This resulted from a bid for independence and a demonstration of innovation. New, less expensive, insulator materials (cycloaliphatic resins) appeared on the market, accentuating the drive to more economic structures. The availability of less expensive insulators also imposed a downward pressure on the prices of the more traditional glass and ceramic insulators.

Cost
insulators

The sudden expansion of Eskom activities to areas closer to the consumer had meant that the available pool of skilled and experienced manpower was too small to be represented in all the new Regions. It was partly because of this skills shortage that a Design Special Interest Group was established within Eskom in 1987. It was established as a forum for the discussion of general design problems, but concentrated on line design at 22kV right from the start.

By 1989 the discussions at the Design Special Interest Group meetings had not come even close to any simplifying conclusions. Each Regional grouping continued to use their old (pre-1985) design, or even produced new designs. No universal standard design existed. From the writer's experience up to that time there also appeared to be no clear and straightforward way of evaluating or comparing the existing configuration designs. There were

also no incontrovertible reasons to force any design to be accepted (or rejected) when compared to any other.

Within Eskom there was, however, an ever-increasing pressure to standardise, not on pole-top configuration designs as such, but on the components used in the designs.

The environmental impact of distribution structures (steel lattice towers from 765kV to 66kV and single pole structures from 88kV down to 11kV) had also been critically examined by Eskom for some time with particular reference to their effect on wildlife. Increased environmental awareness amongst the general public was creating a climate in which Eskom was making every effort to preserve its public image as caretaker of that environment. The death of raptors, such as Cape Vultures, or other endangered species, on distribution structures is not acceptable nowadays.

It was against this background that the research was started. It was intended to produce a set of criteria for the evaluation of the geometry of a conductor configuration. Thus, the best configuration design, of those currently in use in South Africa, could be selected, based on sound engineering and economic reasons.

It was seen that the major factor influencing the design of the line was the geometry or configuration of the conductors at the top of the pole. The position of the conductors relative to each other and to the top of the pole determines the point of action of the resultant wind-load force relative to ground level. The force and its point of action are needed for the calculation of the stress in the pole itself and in the foundation. The configuration also determines the clearance between conductors. The position of the lowest conductor relative to the pole top affects the clearance between that conductor and the ground.

The particular configuration used for a rural distribution line is essentially pre-determined as each Region within Eskom (as mentioned previously) uses its own design.

The method used to keep the conductors in their relative positions, i.e. the pole-top framework or crossarm, needs to be carefully analysed because it and the other components determine the construction and erection costs of the complete structure.

It was decided to compare only intermediate structures in this work. Only self-supporting structures that carried one three-phase circuit were included in the research. This meant that pole-mounted transformers, tee-offs, angle strains and the like were excluded. The logic behind this decision was simply to avoid getting bogged down with comparisons of structures which are probably less than ten percent of the total number of structures used in a line.

1.2 RESEARCH ON WHICH THIS THESIS IS BASED

The research on which this thesis is based was carried out between July 1989 and September 1991.

The writer has been working for Eskom since 1982 and is currently the Design Manager in the Western Cape Region, a position that he has held since 1985. The Design Section has the task of producing the designs required for expansion or modification to the electricity supply network of the Region at voltages of 132kV and below.

The subject of the thesis is, in fact, a self-study topic. The writer, by undertaking the work, has learnt about the technical and economic aspects of overhead distribution line design in general and of single-pole structures and configurations at 11kV and 22kV in particular.

The initial effort in the research was put into establishing what information has been published on the subject of rural line structures at 11kV and 22kV. A large number of conference proceedings, books and journals were consulted. Out of more than 500 papers related to the design of overhead lines, only about 22 were found to relate to an aspect specific to this research. The remainder (approximately 33) of the listed references were more easily obtained as the research by then was more focused on specific sources such as the South African Bureau of Standards. Reference is made to publications by SAIEE, IEEE (USA), IEE (UK), CIGRE, CIREN, EPRI and others.

It was also established, from the literature survey, that similar research was limited, both in the RSA and elsewhere. Only one reference has been found which gives a comparison of pole-top structures at 11kV or 22kV (Macey & Dickson, 1987). Comparisons of three types of structures are made relative to the limiting factors of overturning or excessive fibre stress due to wind load.

Information obtained from the literature survey is also essential for the analysis and evaluation of South African practice as it provides a background and a perspective for the investigation.

Generally, published research papers cover a specific aspect or problem area of distribution line design. The survey of the literature, and the resulting detailed study of the design theory, was therefore most conveniently broken down into sections, each covering a specific topic. Field trips were made by road to construction sites in the Karoo area of the Western Cape Region in order to observe line-building operations. The routes to the construction sites were planned in such a way that photographs could be taken of existing 11kV or 22kV rural line structures in this and other Eskom Regions. Visits to other Regions were used to obtain more information and to take photographs. The writer was able to obtain drawings of the standard Regional structures from his colleagues attending Design Special Interest Group meetings. Data on costing was obtained from within the Design Section and from the Project (Construction) Section in the Western Cape Region and from other Eskom Regions.

1.3 A GUIDE TO THE THESIS

The geometric configurations of intermediate wood-pole structures throughout the world are presented first. Several theories covering aspects of rural line design are then examined. Next, the core subject-matter of this thesis, the comparison and evaluation of poletop geometries, is presented. Finally, the results of the research and the conclusions derived from them are given.

Chapter 2 introduces the reader to a number of the configuration designs currently in use for 11kV and 22kV distribution lines throughout the world. It is divided into two main sections; the first covers twenty-seven South African poletop configuration designs and the second covers twenty-six overseas designs.

Each of the drawings of the South African designs is accompanied by a brief description of the structure and its use. Photographs also illustrate twenty-two of the designs. Only limited comments are made as the analysis of selected configuration designs is made elsewhere. The twenty-six overseas designs are commented on more fully in the text accompanying the drawings than are the South African designs.

Chapter 3 covers nine parameters or factors which have to be taken into consideration when designing a rural line at 11kv or 22kV. They are: conductor clearances, spans, sags and tensions of the conductors, pole strengths, soil strengths, lightning-related design aspects, electrical losses and environmental impact. The design of a line revolves around the selection of a suitable span (the distance between poles). The poletop structure is detailed in a standard (which may be regional or national) and the size of the conductor is determined by the required current-carrying capacity of the line.

Each main section in Chapter 3 covers one of the design parameters or factors except that conductor spans, sags and tensions are grouped together. Information about design methods being used throughout the world was obtained from published literature. The different formulae for each parameter are evaluated and compared in each section.

South African practice is analysed in Chapter 4. Eight current South African (Eskom) designs are selected from the range of ten configurations that were built by or for Eskom during the

period 1986 to 1991. They are fully detailed with respect to construction geometry, dimensions and components.

Each design-limiting parameter (clearance, pole strength, soil resistance, conductor spacing) is examined in terms of the maximum span possible without the allowed limit for that parameter being exceeded. The limitations of each configuration are explored for each of the three most commonly used conductors in South Africa (Fox, Mink and Hare). In addition to these engineering comparisons, other factors such as material and construction costs, maintenance, the effect of lightning, and environmental impact, are taken into account. The results of this evaluation of the poletop configurations used in South African practice are summarised in the same chapter. The limitations of each of these configurations are examined.

Chapter 5 rounds off the thesis by discussing the direct and indirect results of the research. The direct results are those which are in line with its main aims. The indirect results include secondary issues which came to light during the research. Avenues of future design development and research are outlined.

CHAPTER 2

POLETOP CONFIGURATION DESIGNS USED IN PRACTICE

The main purpose of this chapter is to introduce the reader to some of the poletop configuration designs which are in use throughout the world. It contains outline drawings of fifty-three designs of poletop geometry for intermediate structures in use in the distribution of electricity at 11kV and 22kV. Designs are shown in sufficient detail to emphasize major differences. It has not, however, always been possible to explain these differences, as design information is not readily available.

The data presented concentrates on poletop geometry, rather than on structural components such as conductors, poles or foundations. Poletop geometry shows the greatest variation, and therefore presents more opportunities for comparison and comment. The other matters are discussed more fully in Chapter 3 where line design theory is presented and evaluated.

2.1 SOUTH AFRICAN PRACTICE

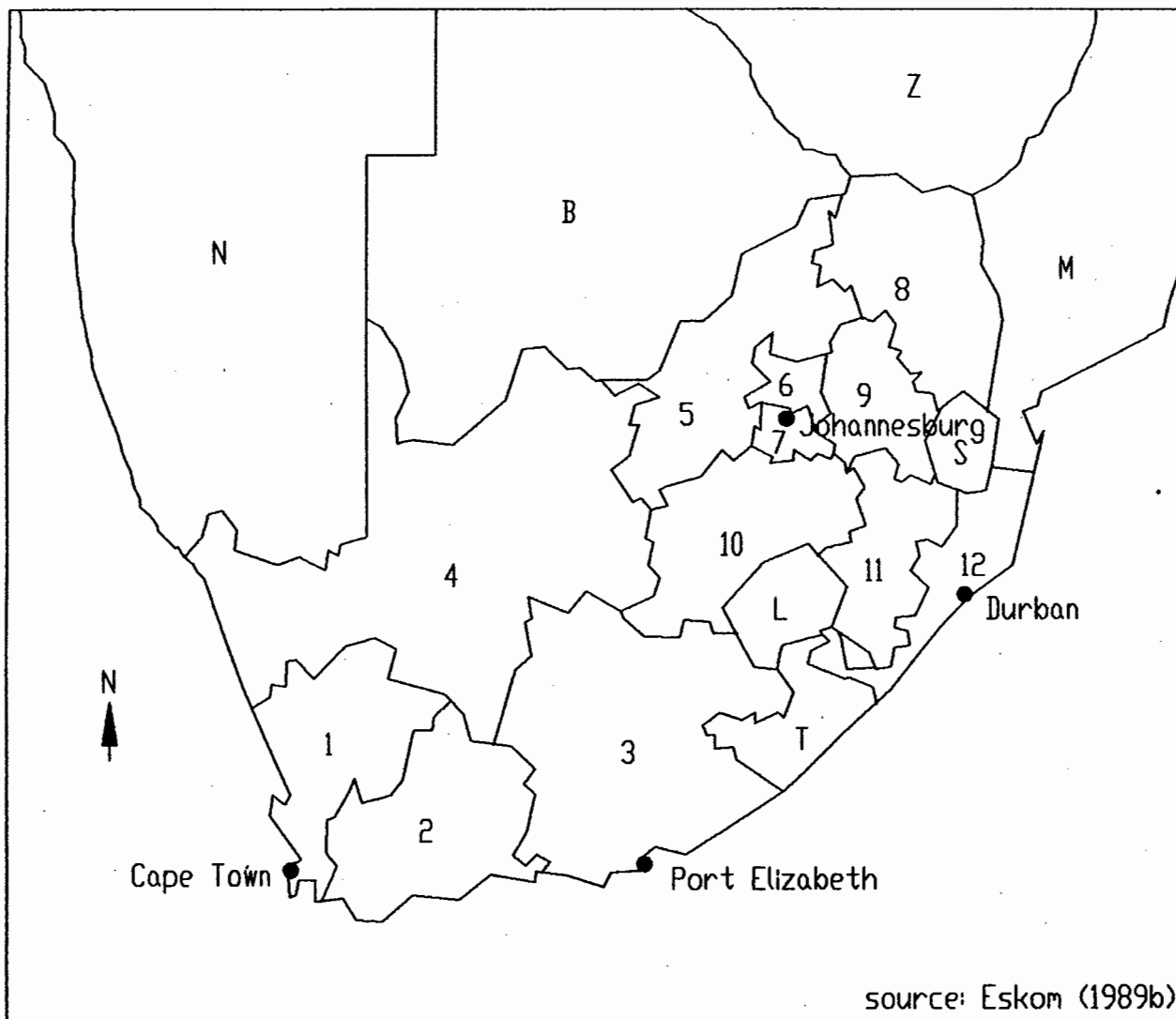
The bulk of the information presented in this Chapter concerns Eskom installations. Twenty out of the twenty-seven designs illustrated are in use in Eskom 11kV and 22kV distribution systems. The remaining seven designs are part of municipal systems. Each illustration is captioned with a short paragraph which gives the design's origin (Eskom Region or municipality), description and use. The Eskom Regions and neighbouring states are shown on Map 2.1.

Insulators and other hardware items (for example spindles) are not discussed (or shown) in detail in this chapter as they do not significantly alter the basic geometry of the design, which is the position of the conductors relative to the poletop. The length of an insulator will affect the conductor spacing on certain of the designs, for example on the vertical offset configuration. The basic structure of the configuration limits the choice of insulator and other hardware. For example, a structure designed for a pin or post insulator cannot generally be used with suspension insulators on all phases, and vice versa.

Some configurations show earthing connections going part-way up the pole, leaving a 300kV BIL (Basic Insulation Level) gap between the conductor and earth. These and the fully-earthed configurations are in use in areas of higher lightning intensity. The influence of lightning on the design of lines and line structures is more fully discussed in Chapter 3, Section 3.7.

The parts count is given for fifteen of the designs shown and is included as an indication of two cost-related factors for these, mainly current, designs. Firstly, the number of stock items that have to be held in the store is related to the parts count. (It is not directly equivalent as a stock item (such as a spindle assembly) could be made up of several components (spindle, spring washer and nut), each counted separately in the parts count.) The greater the number of different stock items or the more items that have to be stored, the larger must be the store and hence the cost of storage, the cost of operation, handling, transport and so on. The actual purchase cost of the individual stock item is a separate issue. Secondly, the amount, and hence the cost, of labour involved bears a direct relation to the number of parts that have to be assembled. These cost-related matters are discussed more fully in Chapter 4.

The parts count for each design excludes the conductors and conductor ties but includes, as separate items, each bolt, nut or washer. All the staples for fixing earth wires are taken as one



Eskom Distribution Regions

1. Western Cape Region
2. Southern Cape Region
3. Eastern Cape Region
4. Northern Cape Region
5. Western Transvaal Region
6. Central Transvaal Region
7. Southern Transvaal Region
8. North-Eastern Region
9. Eastern Transvaal Region
10. Orange Free State Region
11. Western Natal Region
12. Eastern Natal Region

Neighbouring States with own Electricity Distribution Agencies

- N : Namibia
- B : Botswana
- Z : Zimbabwe
- M : Mozambique
- S : Swaziland
- L : Lesotho
- T : Transkei

ESKOM REGIONS and NEIGHBOURING STATES

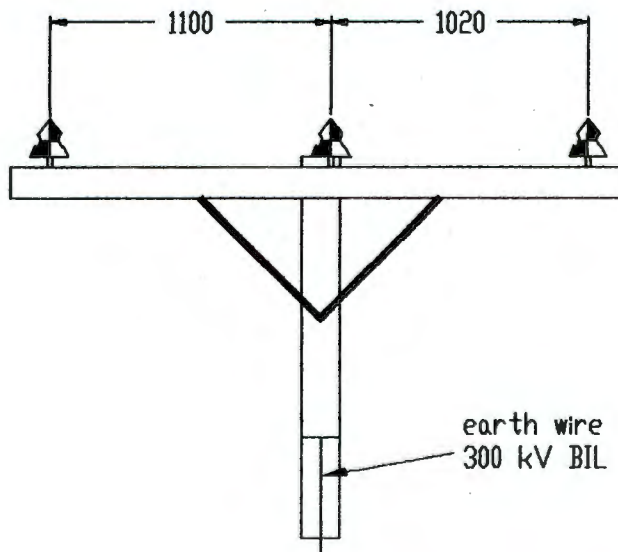
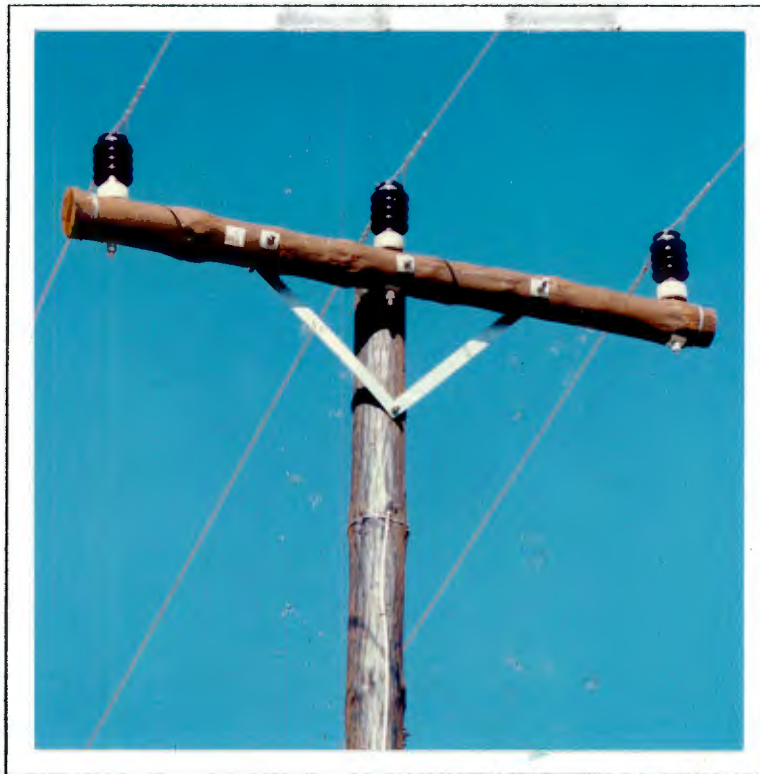
MAP 2.1

item. The parts count is taken from design drawings for the particular structure (and was therefore available for only those designs for which drawings were obtained). It is easy to reduce the number of parts used in a particular configuration by leaving out items which do not significantly affect the initial structural integrity. These items include lock washers, flat washers and lock nuts. However, performance of the line over its lifetime may be affected.

Drawings have not been done to an exact scale and are provided only to depict the geometry of the design and to give comparative dimensions for conductor spacing. The comments given in the text below supplement or expand on the information given in each diagram.

The 11kV and 22kV lines built by or for Eskom during the period from 1989 to 1991 include a range of ten configuration designs, shown in Figures 2.01 to 2.08. The common factor amongst eight of these designs is that they have some measure of lightning-related insulation co-ordination. For the most part a gap with a basic insulation level (BIL) of 300kV is used.

The design shown in Figure 2.01 is based on the old BS1320 (1946) design (Figure 2.20). The spindle of the centre insulator in this horizontal configuration has been moved to one side in order to miss the bolt holding the crossarm to the pole.



DESCRIPTION: Wooden crossarm with twin steel flat braces. Flat horizontal conductor configuration. Spindles are not bonded. Small-gap earthed construction. Offset of centre insulator because of crossarm bolt / centre spindle position.

USE: Current design in Eskom Northern Cape Region. Similar to British designs. Similar designs are used in Eskom Eastern Natal and Eastern Cape Regions, both designs being of unearthed construction.

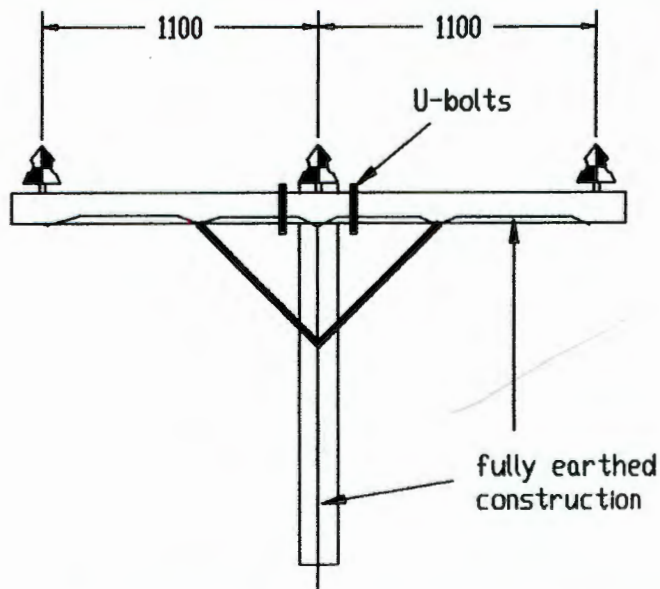
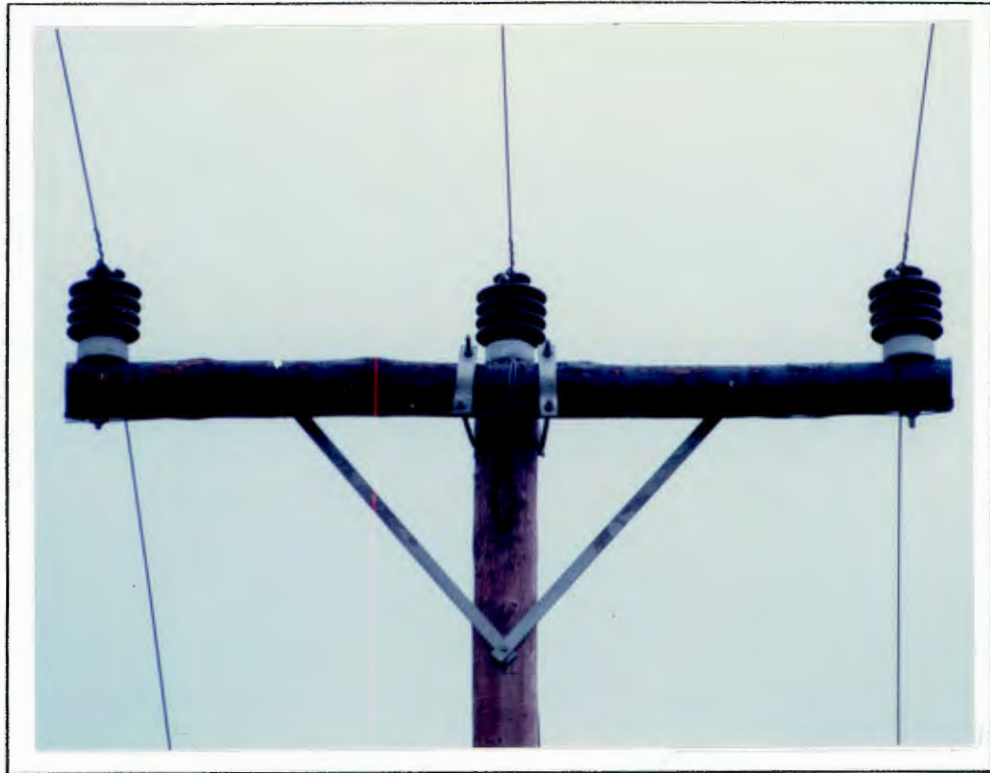
PARTS COUNT: 57 (300kV BIL)

HORIZONTAL CONFIGURATION

FIGURE 2.01

Figure 2.02 shows a fully-earthed woodpole structure with a wooden crossarm. The metalwork of the structure (all bolts, spindles and braces) has been bonded together and earthed. An additional precaution of using u-bolts to secure the crossarm to the pole has been taken. A bolt through a woodpole could cause splitting of the pole as the result of a lightning strike. It would have been simpler, more reliable and less labour intensive to use a steel crossarm or frame such as shown in Figures 2.05 and 2.08 instead of a wooden crossarm.

The use of a steel crossarm or frame has another advantage. The spindle mounting-end (that goes through the crossarm) need be available in only one standard length because a fixed thickness of steel is used. A spindle for use on a wooden crossarm (or pole) would have to be available in (say) three lengths of mounting-end because of the varying diameters of the timber used.



DESCRIPTION: Wooden crossarm with twin steel flat braces. Flat horizontal conductor configuration. Fully-earthed construction. Crossarm secured to pole with u-bolts and straps to prevent pole splitting due to lightning strikes.

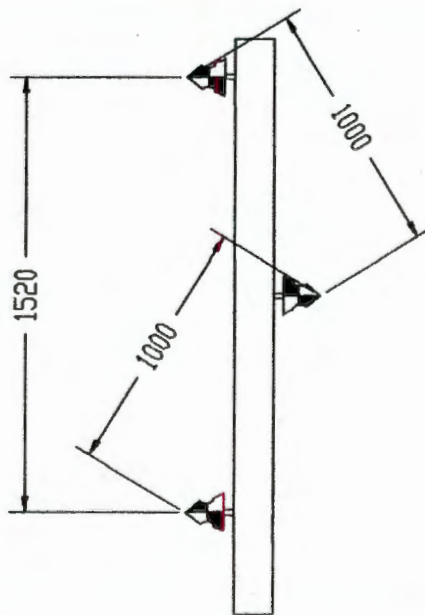
USE: Current design in Eastern Natal Region.

PARTS COUNT: 74 (fully earthed)

HORIZONTAL CONFIGURATION : HIGH LIGHTNING AREAS

FIGURE 2.02

In Figure 2.03 the photograph of the offset vertical configuration shows clearly that a double nut and spring washer were used to secure the insulator spindle to the pole. It is assumed that the use of only a single nut on the insulator spindle makes it possible for the nut to work loose and fall off (due to the action of the wind on the conductor and hence on the insulator spindle). The wood of the pole may also be compressed to some extent. The spindle could pull out of the pole and hence result in a phase-to-phase or phase-to-earth fault. The second nut is used to lock the first nut so that it will not loosen.



DESCRIPTION: No crossarm. Insulator spindles bolted directly to the pole. Unearthed or small-gap earthed construction. Slightly better ground clearance for the same length of pole compared to vertical configuration.

USE: Current design in Eskom Western, Eastern and North-Eastern Transvaal Regions. Also used (unearthed) by Wilderness Municipality.

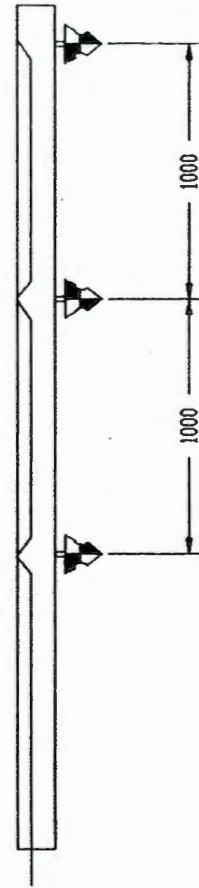
PARTS COUNT: 27 (fully earthed); 24 (300kV BIL); 22 (unearthed)

VERTICAL OFF-SET CONFIGURATION

FIGURE 2.03

Figure 2.04 shows the wire bonding the insulator spindles of the vertical configuration together. It can be clearly seen to the left of the pole in the photograph.

University of Cape Town



DESCRIPTION: No crossarm. Insulator spindles bolted directly through the pole. Fully-earthed construction. Also used with stays for angles of up to 17 degrees for Fox conductor. Least ground clearance of all designs for the same length of pole.

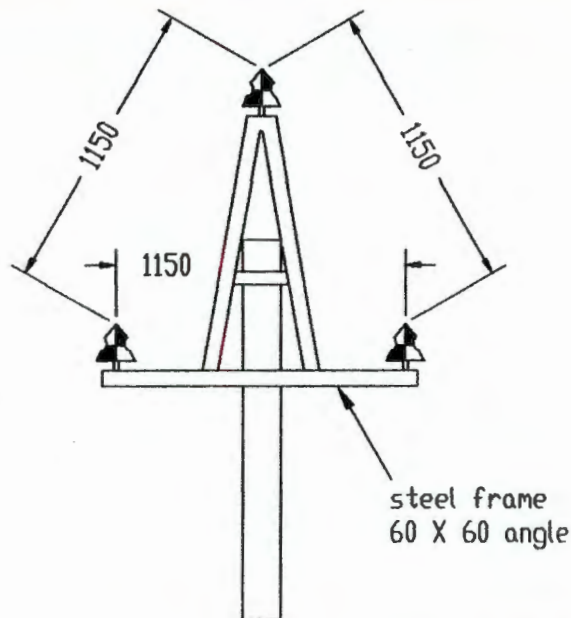
USE: Current design in Eskom Eastern Natal and Eastern Transvaal Region. Similar unearthed design in use in North-Eastern Transvaal Region.

PARTS COUNT: 27 (fully earthed); 22 (unearthed)

VERTICAL CONFIGURATION

FIGURE 2.04

Figure 2.05 shows the steel A-frame configuration which is used in areas of low lightning intensity. It is not deemed possible to use this configuration where the insulation co-ordination of the line calls for a 300kV BIL as the spindles are bonded by being bolted to the steel frame. However, where complete bonding of the spindles is required, a steel crossarm would offer certain advantages (as noted with respect to the configuration shown in Figure 2.02).



DESCRIPTION: Galvanised steel frame fabricated from 60mm angle-iron. Near full 120 degree delta configuration. The same frame is used for 11kV and 22kV with the appropriate insulator. A unique design; out of the nearly fifty different designs from nine different countries it is the only design which uses a one-piece steel frame for a full delta configuration. Spindles are automatically bonded as it is a steel structure. Only one length of spindle mounting-end is needed. Used as an unearthed construction.

USE: Current design in Eskom Western and Southern Cape Regions. In use in various forms since 1962.

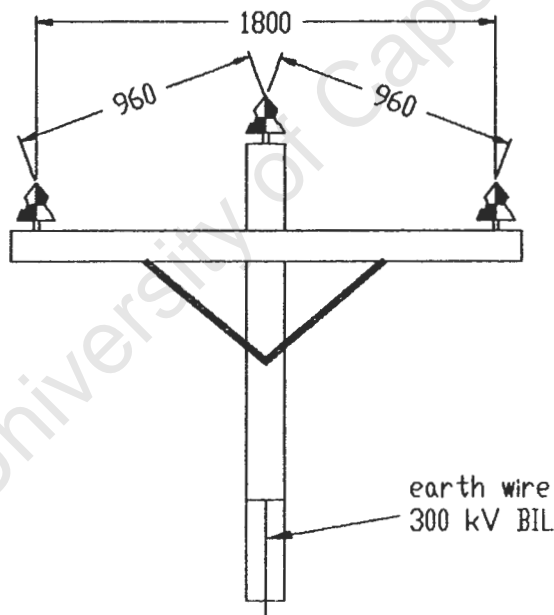
PARTS COUNT: 22 (unearthed)

A - FRAME DELTA CONFIGURATION

FIGURE 2.05

Figure 2.06 illustrates the horizontal delta configuration

Two "bird-friendly" versions of this configuration are shown in Figure 2.07. The bird is prevented from perching on the crossarm by the inverted braces (A) or the outer conductors are suspended from the crossarm to prevent centre- to outer-phase contact (B). The design shown in Figure 2.07A has been discontinued as it was found that the inverted steel braces decreased the basic insulation level between phases, thus creating a phase-to-phase flashover path instead of the preferred phase-to-earth path.



DESCRIPTION: Wooden crossarm with twin steel braces. The centre insulator is mounted on the pole above the crossarm level. Short-gap (300kV BIL) earthed construction.

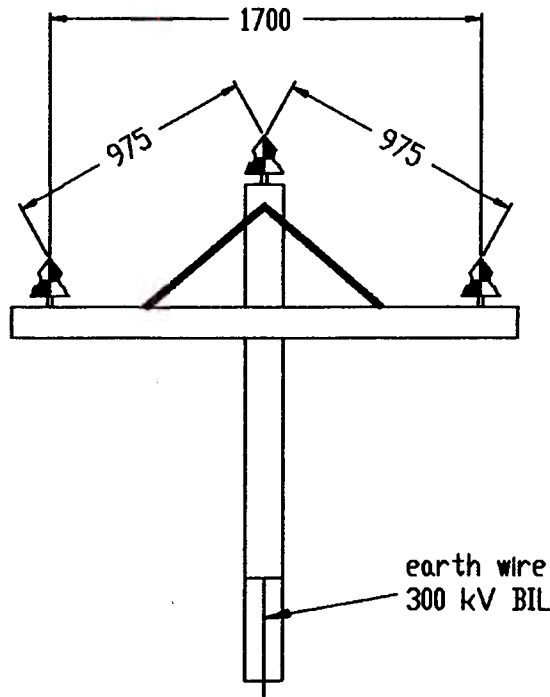
USE: Current design in Eskom Western Natal and Western Transvaal Regions. Similar to USA (Rural Electrification Administration) practice.

PARTS COUNT: 64 (300kV BIL)

photo: Herman Smit

HORIZONTAL DELTA CONFIGURATION

FIGURE 2.06

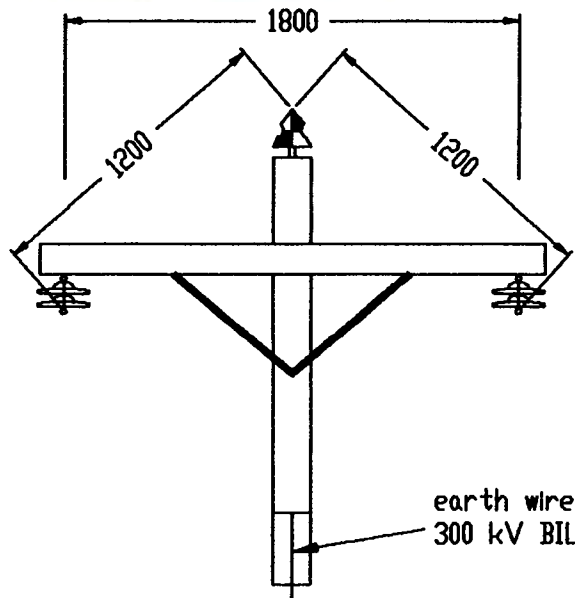


DESCRIPTION: Based on a standard design (Figure 2.06), this design inverts the twin steel braces in order to prevent large birds perching on the crossarm. Short-gap earthed construction.

USE: A design used in the Eskom Orange Free State Region in 1990.

PARTS COUNT: 64 (300kV BIL)

(A)



DESCRIPTION: Based on a standard design (Figure 2.06), this design uses two sets of suspension insulators to move the outer conductors to below the crossarm. In contrast to the above design this design will permit large birds to perch on the crossarm but without bridging two phases.

USE: Current design in Eskom Western Natal Region.

PARTS COUNT: 71 (300kV BIL)

(B)

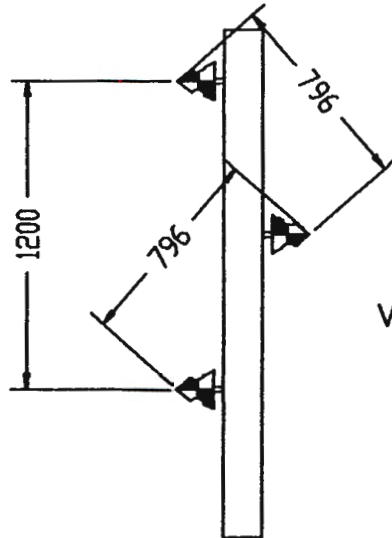
**HORIZONTAL DELTA CONFIGURATIONS
MODIFIED TO BE "BIRD-FRIENDLY"**

FIGURE 2.07

Figure 2.08 shows the latest Eskom designs (May 1991). The aim of making the changes to the original designs was to increase the maximum span for which they could be used.

The distances between the insulators in the vertical offset configuration was decreased so that the lowest conductor was raised, thereby increasing the ground clearance and hence the maximum span.

The A-frame was modified by increasing the separation between the outer phases and raising them. Both changes result in an increased maximum span.



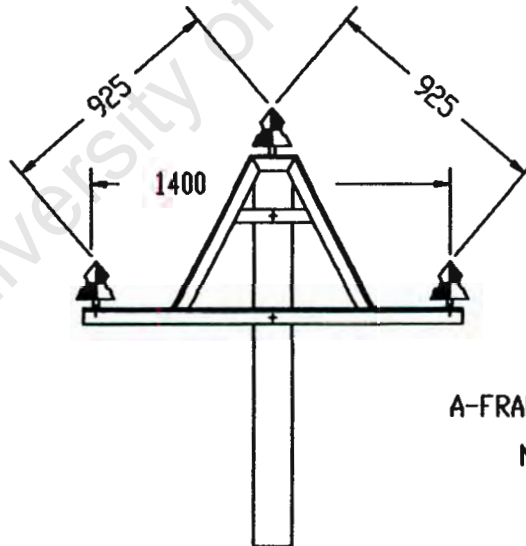
VERTICAL OFF-SET CONFIGURATION
NEW DESIGN

DESCRIPTION: Based on a standard design (Figure 2.03), the change in conductor spacing has permitted a gain of 0,32m in ground clearance and hence an increase in possible span.

USE: One of the two new Eskom standard designs which will be used throughout Southern Africa on all new lines at 11kV and 22kV.

PARTS COUNT: 27 (fully earthed); 24 (300kV BIL); 22 (unearthed)

(A)



A-FRAME CONFIGURATION
NEW DESIGN

DESCRIPTION: Based on a standard design (Figure 2.05), the change to the overall configuration (wider and flatter) was made in to increase the possible span. Unearthed construction.

USE: One of the two new Eskom standard designs which will be used throughout Southern Africa on all new lines at 11kV and 22kV.

PARTS COUNT: 22 (unearthed)

(B)

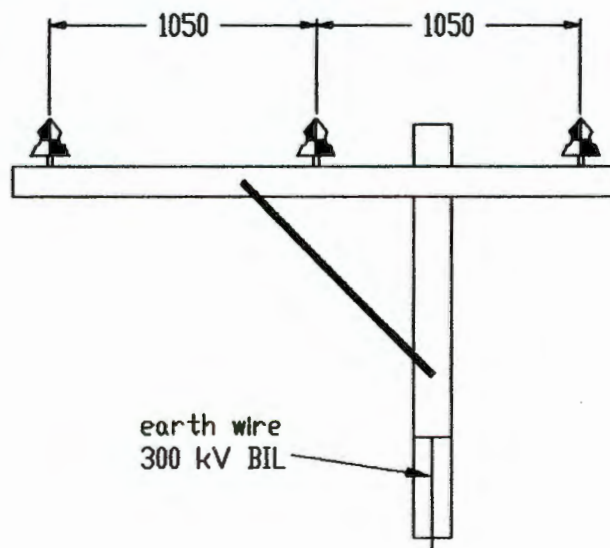
NEW STANDARD ESKOM DESIGNS : MAY 1991

FIGURE 2.08

Figures 2.09 to 2.19 are of poletop configurations which are in use in existing South African 11kV and 22kV distribution systems, but which are not used for new lines.

The horizontal offset configuration shown in Figure 2.09 appears to be mechanically incorrect as a flat brace should be in tension, that is, attached to the short end of the crossarm. The configurations used by George Municipality (Figure 2.10A) and Eastern Cape Region (Figure 2.15A) are similar to this design except that the latter is fitted with an overhead shield wire for lightning protection.

Figures 2.10B and 2.11 show 11kV structures which typify the use of the swan neck spindle, which enables the insulator to be mounted vertically without a crossarm being used.



DESCRIPTION: Wooden crossarm with a single flat steel brace. Flat horizontal conductor configuration. Small-gap earthed construction. Spindles are not bonded.

USE: Installed design, replaced by the current symmetrical horizontal design, in Eskom Northern Cape Region. Similar to the earthed construction used in Eskom in the former Rand and DFS Region.

PARTS COUNT: 49 (300kV BIL)

HORIZONTAL OFFSET CONFIGURATION

FIGURE 2.09



GEORGE MUNICIPALITY

DESCRIPTION: Horizontal asymmetrical conductor spacing. Wooden crossarm. Single tubular brace. Spindles not bonded.

USE: Rural distribution within municipal area of supply

(A)



WILLISTON MUNICIPALITY

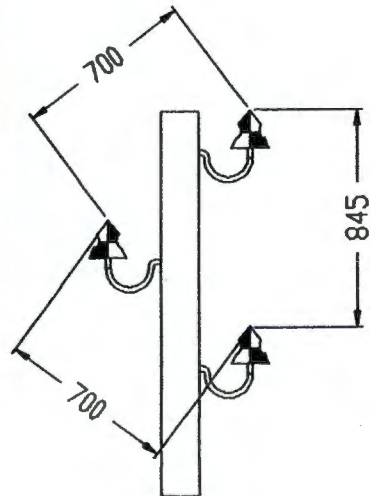
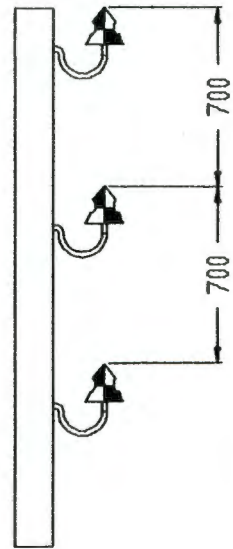
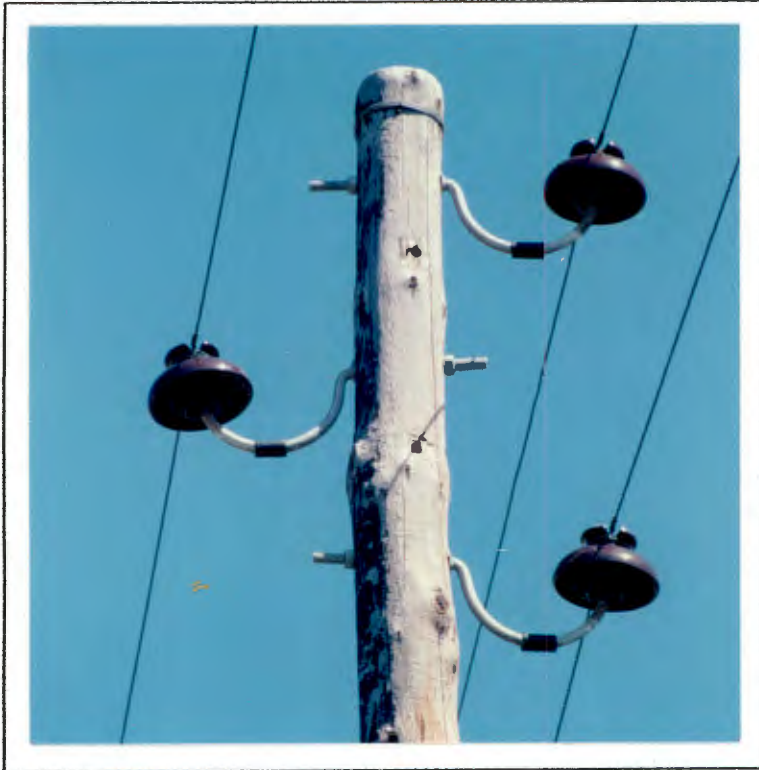
DESCRIPTION: Combination of swan neck and vertical insulator spindles. Other poles in the same line use three swan neck spindles. The top (vertical) spindle fixed into the end-grain of the pole; not a secure design.

USE: Overhead line feeding an outlying municipal water pump.

(B)

EXAMPLES OF OVERHEAD LINES IN USE BY MUNICIPALITIES

FIGURE 2.10



DESCRIPTION: Vertical and vertical off-set configurations using swan neck spindles so that the insulators are vertical. Not bonded or earthed. Triangular, not full delta, configuration.

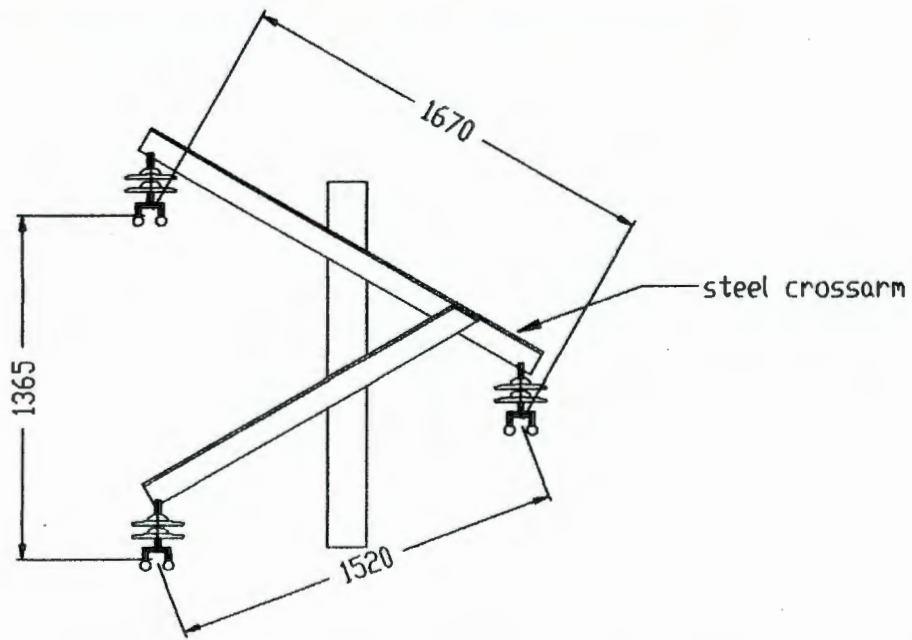
USE: Installed designs, Wilderness and Williston Municipalities.

PARTS COUNT: 13 (unearthed)

SWAN NECK SPINDLE: VERTICAL AND OFF-SET CONFIGURATION

FIGURE 2.11

Figure 2.12 illustrates the steel wishbone structure used for comparatively large power flows over short lines at 11kV. Twin Hare conductor will supply 11,8MVA (compared to 4,7MVA for single Mink conductor) over a distance of 4km for a volt drop of 10% (Lay, 1990). The structure cost, because of the suspension insulators and the fittings required for the double conductor arrangement, is comparatively high. Spans are of the order of 60m.



DESCRIPTION: Galvanised steel 100mm angle-iron frame designed for double Hare conductor. Unearthed construction. Triangular, not full delta, conductor configuration.

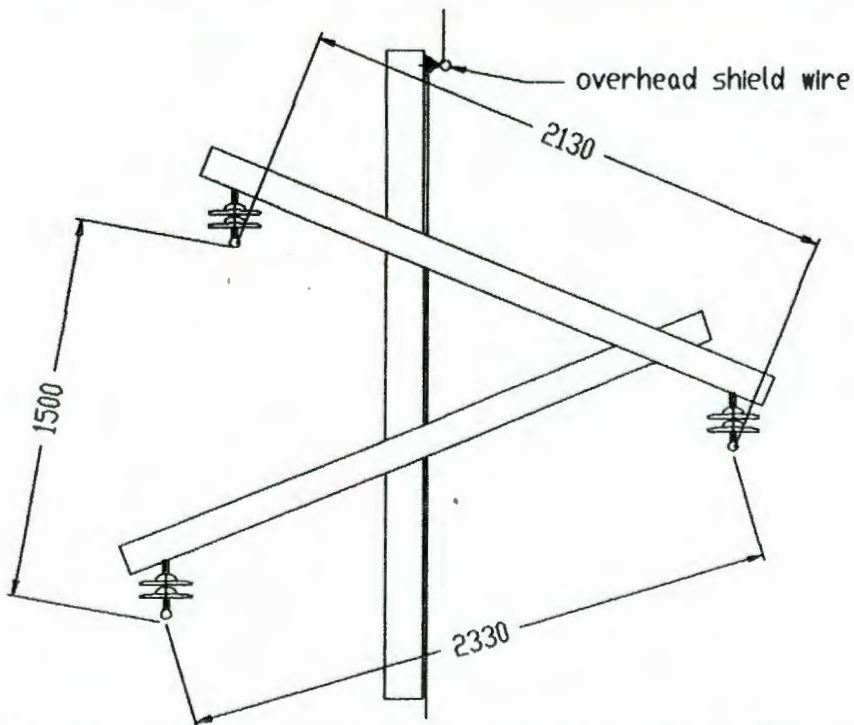
USE: Installed design, Eskom Western and Southern Cape Regions

PARTS COUNT: 35 (unearthed)

STEEL WISHBONE CONFIGURATION

FIGURE 2.12

Figures 2.13, 2.14 and 2.15A are all of structures used in the Eastern Cape Region. The configurations all use "lightning-conductor-like" spikes (which are unnecessary) above the shield wire. All three configurations are in use in an area near Victoria West in the Karoo. Both the structures in Figures 2.13 and 2.14 are big structures in terms of conductor separation (2,13m and 1,65m respectively) and yet the spans used were of the order of only 130m (possibly limited by ground clearance). The span limit for the new vertical offset structure is of the order of 150m for a very much simpler and cheaper structure. Overturning moment for the wooden wishbone structure (Figure 2.13) would be comparatively high because of the pole length and the crossarm area exposed to wind load. It is also an expensive structure as it uses three sets of glass disk insulators. The portal (double pole) structure (Figure 2.14) is even more expensive particularly when the line capacity or span appears to be no greater than that of a line using an A-frame crossarm (Figure 2.05).



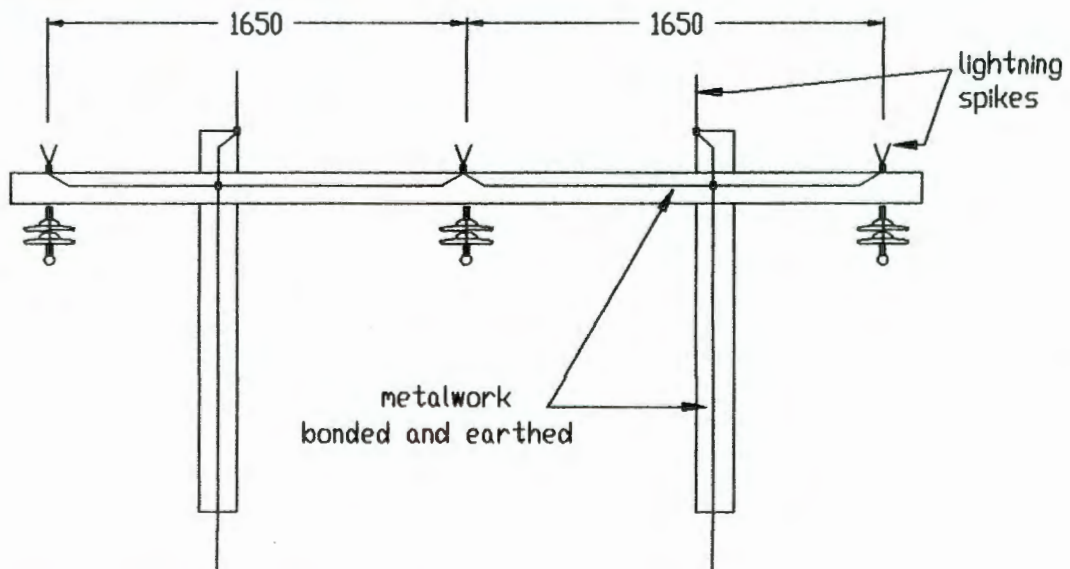
DESCRIPTION: Wooden wishbone crossarms with overhead shield wire. "Lightning spikes" attached to shield wire, which should be earthed. Triangular, ie not full delta, conductor configuration.

USE: Installed design in Eskom Eastern Cape Region. Similar to designs without shield wire used in Eskom in the former Rand and DFS Region.

PARTS COUNT: 59 (shielded)

WOODEN WISHBONE TRIANGULAR CONFIGURATION

FIGURE 2.13



DESCRIPTION: Wooden double-pole, single crossarm portal construction. Horizontal conductor configuration. Earthed with "lightning spikes" above pole tops and on insulator fittings.

USE: Installed design in Eskom Eastern Cape Region. Similar design with double overhead shield wire in use in Eastern Transvaal Region.

PARTS COUNT: 56 (fully earthed)

WOODEN PORTAL CONFIGURATION

FIGURE 2.14



ESKOM EASTERN CAPE REGION

DESCRIPTION: Wooden asymmetrical crossarm with single angle-iron brace. Horizontal conductor configuration. Overhead shield wire with "lightning spike". Unearthed (at this pole).

USE: Rural 11kV distribution line.

A



ESKOM WESTERN CAPE REGION

DESCRIPTION: Steel channel crossarm. Steel pole fitted with conductor catchers for the centre phase. Earth wire below crossarm. 33kV insulator retained for 11kV line.

USE: Old 33kV line re-used for 11kV rural distribution backbone.

B

VARIOUS RURAL DISTRIBUTION STRUCTURES IN USE IN ESKOM REGIONS

FIGURE 2.15

Figures 2.15B, 2.16A, 2.16B, 2.17A and 2.17B show five configurations which are included to illustrate the re-use of lines which were originally built to operate at a different voltage. These lines used to be the main feeders in this area of the Western Cape Region of Eskom and when the 33kV network voltage was discontinued the line operating voltages were changed to 11kV and the lines became "Farmers' Feeders".

The configuration structures shown in Figures 2.17 and 2.18A all use steel channel crossarms. The crossarms were designed for steel poles (such as in Figure 2.17A) and were clamped to the pole. The use of wooden poles meant that they could be bolted or clamped to the pole.

A designer's common fear, that structures would fail if not properly built with all the necessary braces, lock washers and other "security" hardware, can apparently be allayed by the structure shown in Figure 2.18B!



ESKOM WESTERN CAPE REGION

DESCRIPTION: Steel angle-iron wishbone crossarm. Porcelain disk insulators for 22kV. Overhead earth wire. Fully earthed and bonded construction.

USE: Used for rural distribution 11kV backbone.

A



ESKOM WESTERN CAPE REGION

DESCRIPTION: Bow fitting suspension structure on a steel pole. Three glass disk insulators for 33kV. Overhead earth wire not fitted.

USE: Old 33kV line re-used for 11kV rural distribution backbone.

B

VARIOUS RURAL DISTRIBUTION STRUCTURES IN USE IN ESKOM REGIONS

FIGURE 2.16



ESKOM WESTERN CAPE REGION

DESCRIPTION: Steel channel crossarm and half-crossarm clamped to steel pole. 11kV line, originally below a 33kV line on upper part of pole (removed).

USE: 11kV rural distribution backbone.

(A)



ESKOM WESTERN CAPE REGION

DESCRIPTION: Steel channel crossarm bolted to wooden pole and fitted with single flat steel brace. U-bracket at top of pole for insulator. 33kV insulators.

USE: Old 33kV line re-used for 11kV distribution backbone.

(B)

VARIOUS RURAL DISTRIBUTION STRUCTURES IN USE IN ESKOM REGIONS

FIGURE 2.17



CAPE TOWN CITY COUNCIL

DESCRIPTION: Steel channel crossarm. Delta conductor configuration. Twin steel braces. Crossarm and top spindle clamped (not bolted) to pole. Earth wire below conductors. Small angle stayed structure.

USE: Limited amount of overhead distribution lines within the Cape Town Municipal area.

A



PORT SHEPSTONE MUNICIPALITY

DESCRIPTION: Horizontal square wood crossarm. No cross braces.

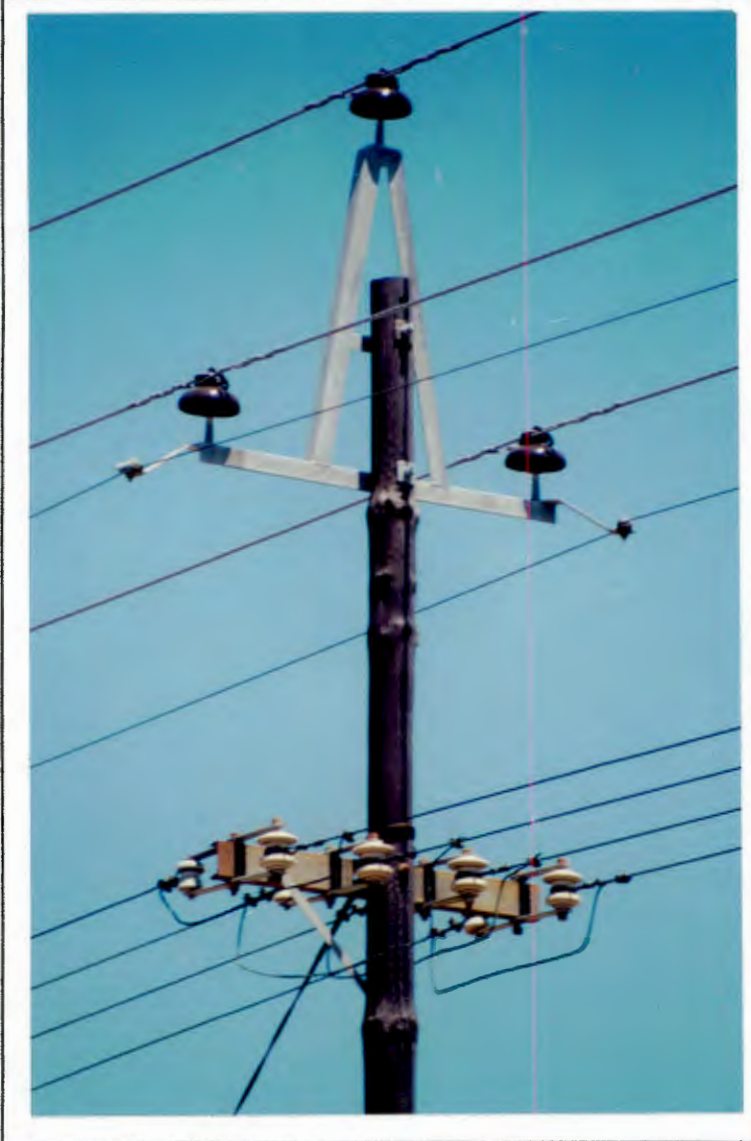
USE: Generally a temporary structure because it is not stable for long-term use.

B

EXAMPLES OF OVERHEAD LINES IN USE BY MUNICIPALITIES

FIGURE 2.18

Figure 2.19, the last illustration of a structure in this section on South African practice is typical of the distribution lines in some of the peri-urban areas of the Western Cape. The line was originally built by Eskom to carry the high-voltage 11kV feed into the area and also to support the 380V 3-phase 4-wire low-voltage network to the consumers. This network was subsequently taken over by the local municipality.



BRACKENFELL MUNICIPALITY

DESCRIPTION: Conventional A-frame plus outrigger brackets for guard wires, fitted at the top of the pole. Low voltage 380volt 3 phase 4-wire system mounted below.

USE: Peri-urban reticulation for plot owners. Overhead system originally installed by Eskom and later sold to the municipality.

PERI-URBAN DISTRIBUTION STRUCTURE: HIGH VOLTAGE PLUS LOW VOLTAGE CIRCUITS

FIGURE 2.19

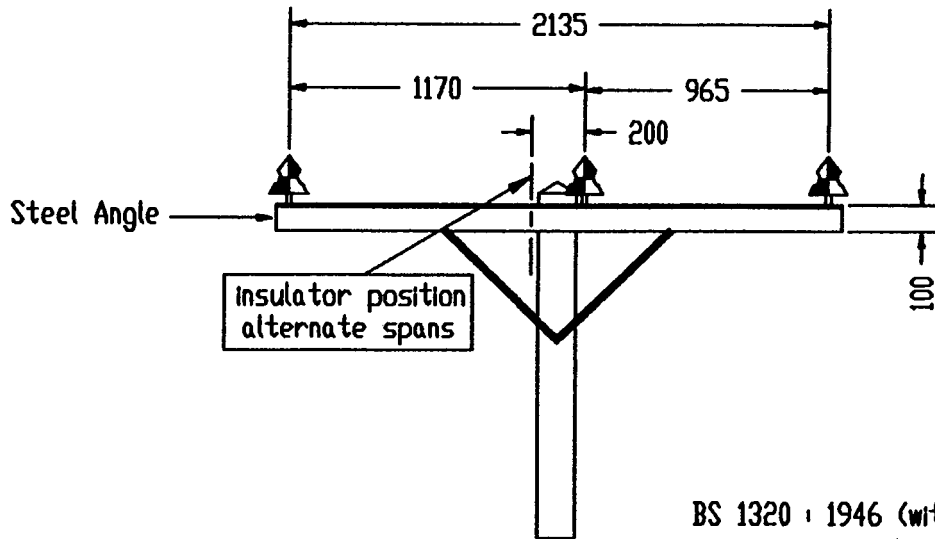
2.2 REPRESENTATIVE OVERSEAS DESIGNS

This section illustrates some overseas poletop configuration designs. The information shown in the drawings has been obtained from various sources which range from published standards to journal articles. The dimensions have, in some cases, been scaled from pictures or drawings and are therefore not accurate.

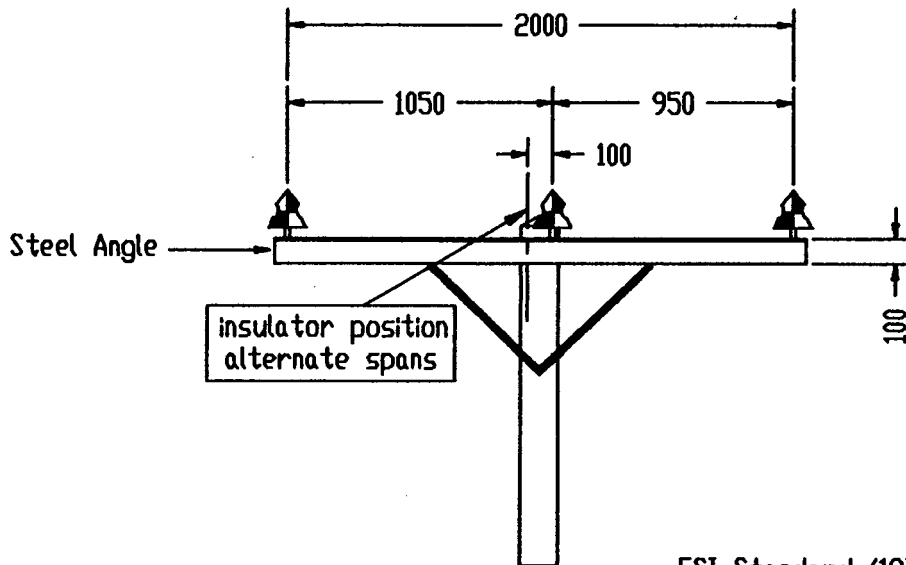
Each individual sketch is captioned with details of the design origin, type and voltage, where these are available. All designs use wooden poles, except where noted.

Several of the designs shown use crossarms that are machined to a specific standard size with rectangular or square cross-sections. This has the advantage that only one size of insulator spindle need be used as there is no variation in the thickness of the crossarm as would be the case with a round (unmachined) crossarm.

Figure 2.20 presents two examples of British standard designs. BS1320 (1946) included wooden crossarms of square cross-section (762mm average conductor spacing) and steel angle crossarms (1068mm average conductor spacing) as part of the range of designs. The new standard (ESI, 1974) that replaces BS1320 (1946) includes only designs for steel angle crossarms similar to those in the old standard. The middle insulator in both standards is moved from one side of the crossarm to the other on alternate spans. The alternate middle position is used so that the average conductor spacings from the middle conductor to the outer conductors are equal.



BS 1320 : 1946 (withdrawn)
 11m pole planted 1,83m
 max. span 103m for 32sq mm Cu

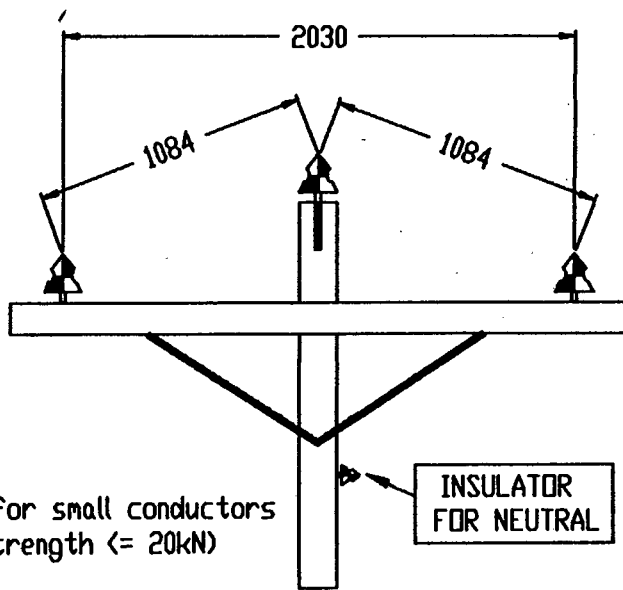


ESI Standard (1974)
 11m pole planted 1,8m
 max span 94m for 32sq mm Cu
 or 107m for 25sq mm ACSR

11kV INTERMEDIATE STRUCTURES
 BRITISH STANDARD DESIGNS

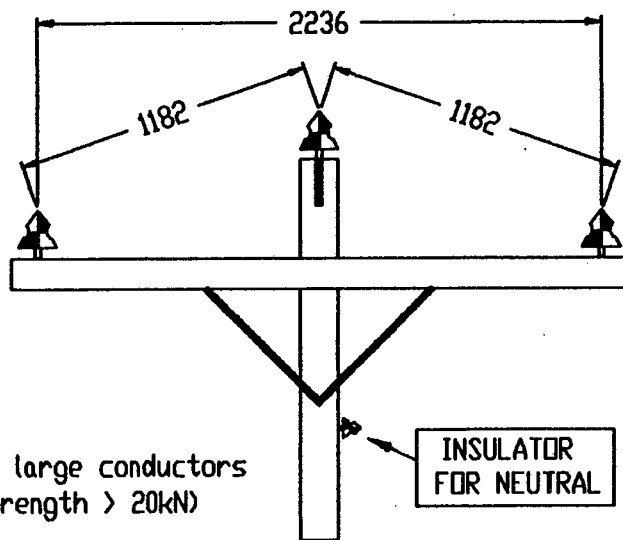
FIGURE 2.20

Figure 2.21 illustrates the fact that nearly all REA (1988) designs have a triangular configuration of the phase conductors where single insulators are used per conductor. Double insulators and double crossarms can be used where greater strength is required because of increased mechanical loading. Such increased loading could be due to a larger conductor being used. Wooden crossarms of rectangular cross-section are used. Provision is made for a neutral conductor, either below the crossarm (triangular configuration) or on the cross-arm in a horizontal configuration. The neutral conductor is provided to allow single phase (line plus neutral) lines to be teed off the main three-phase feeder. The neutral conductor is earthed ("grounded") at multiple points and can also serve as the common neutral for low-voltage circuits underneath the high-voltage conductors on the same pole. Vertical configurations are used on dead-ends or angles but not as intermediate structures.



construction for small conductors
(breaking strength $\leq 20\text{kN}$)

rectangular section
wooden crossarms



construction for large conductors
(breaking strength $> 20\text{kN}$)

(REA, 1988)

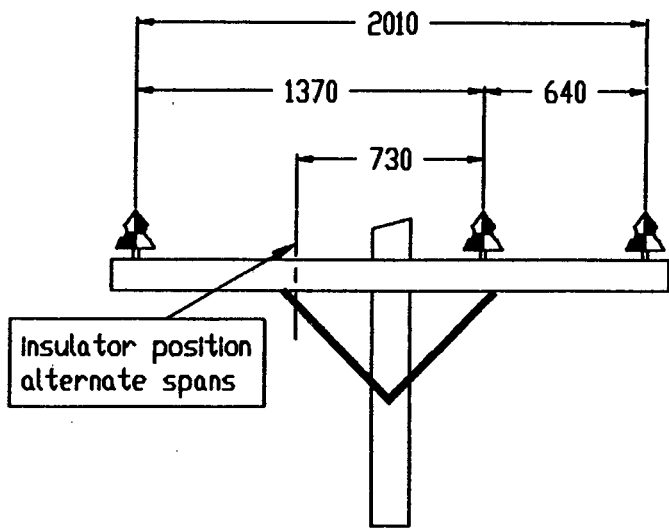
UNITED STATES DEPARTMENT OF AGRICULTURE : RURAL ELECTRIFICATION ADMINISTRATION

REA Bulletin 50-5(d-803) 1969 - updated 1988

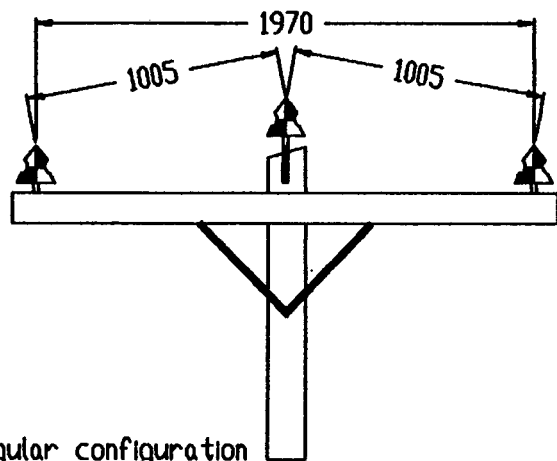
Specifications and Drawings for 14.4/24.9kV Line Construction

FIGURE 2.21

Brazilian designs (Figure 2.22) are derived from those in the USA, where wooden crossarms are used. These designs (Nolasco, 1989) include both horizontal and triangular configurations and provision is made for a neutral conductor. The position of the centre insulator on the horizontal configuration is moved from one side of the crossarm to the other on alternate spans. The reason for the comparatively large displacement of the centre insulator is not clear as there is no (obvious) engineering reason.



horizontal configuration



triangular configuration

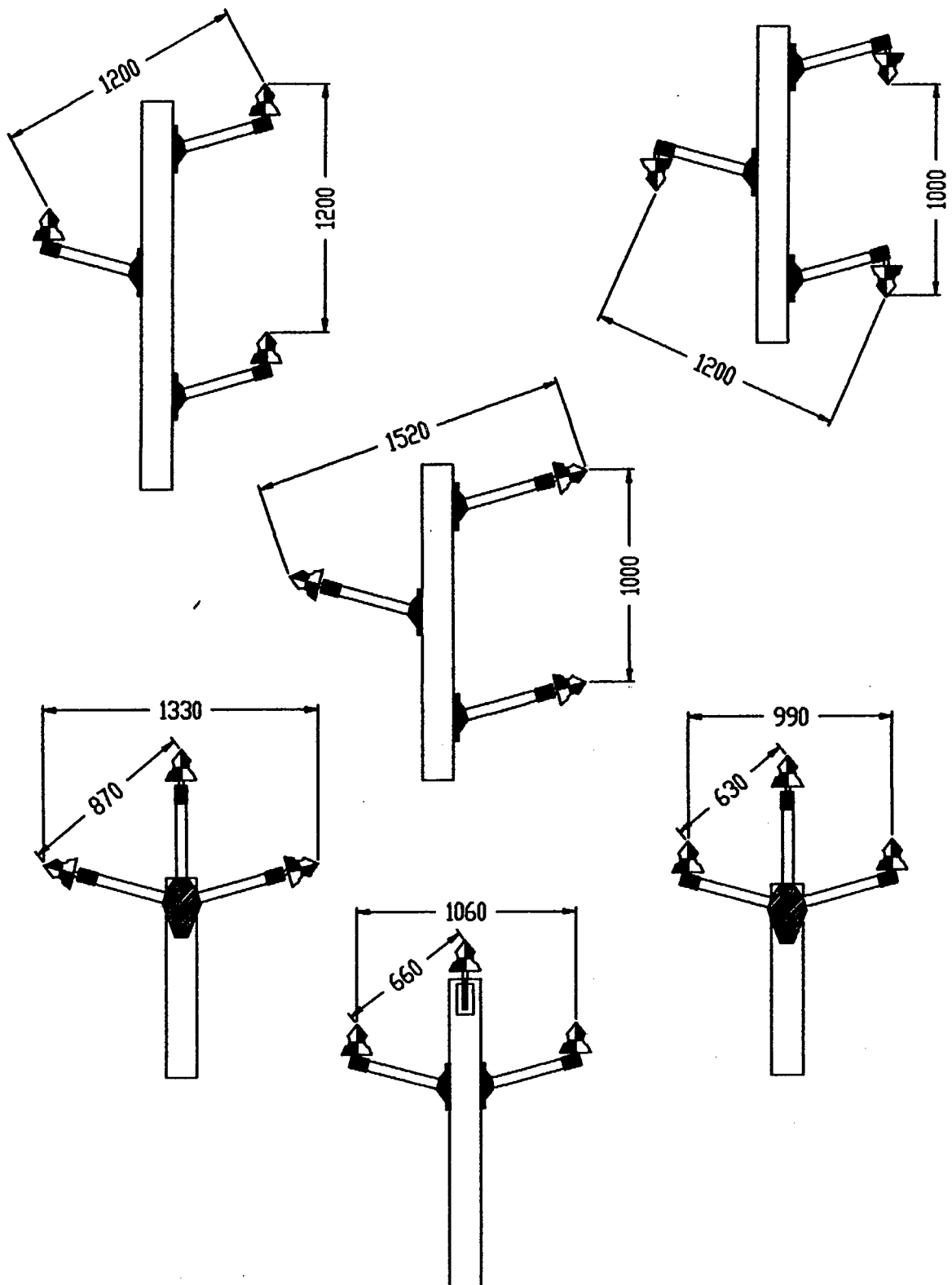
(Nolasco, 1989)

rectangular section
wooden crossarms

11kV INTERMEDIATE STRUCTURES
BRAZILIAN DISTRIBUTION PRACTICE : CEMIG, MINAS GERAIS, BRAZIL

FIGURE 2.22

Figure 2.23 shows a selection of the crossarms and standoffs made by A. B. Chance in the U.S.A. (A. B. Chance, 1982). The drawings serve to illustrate the number of geometric arrangements possible with this type of product. The use of only one size of standoff (that is one stock item) does not limit the user to only one configuration. The standoffs can be fitted to the pole in any position or number to suit requirements for conductor spacing, ground clearance or other special circumstances.



(Chance, 1982)

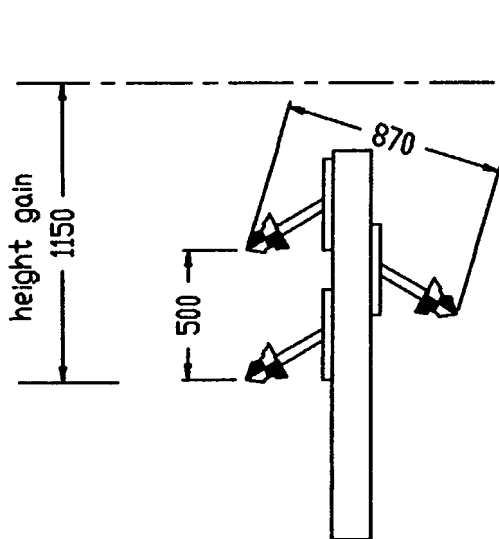
11kV INTERMEDIATE STRUCTURES
 USA : PROPRIETARY CROSSARMS AND STANDOFFS
 Reinforced epoxy rods fitted to aluminium bases and ferrules
 FIGURE 2.23

Figure 2.24 illustrates the four European designs discussed below. Two are for covered conductor (Sweden and Finland) and two are for bare conductor (Switzerland and Germany). Comparison of the two structures within each group with one another brings one important feature to light. This is that the use of a complete crossarm assembly attached to the top of the pole (such as shown for Sweden or Germany) has the benefit of height gain. This means that shorter poles can be used for the same spans and ground clearances or that longer spans can be used for the same poles and still maintain the same ground clearances. The use of a "pre-assembled" crossarm also decreases the amount of construction time in the field.

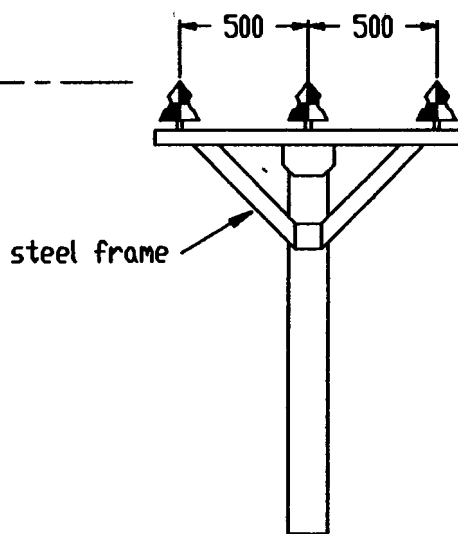
The Finnish standoff is made of steel, in contrast to the USA standoff, which is of reinforced epoxy. The Swiss design shown uses a swan neck spindle for the insulator.

The Finnish designs (Lehtinen, et al., 1989) and the Swedish designs (Andersson, et al., 1989) are for XLPE covered conductor. The use of this conductor is of particular benefit for several reasons. Service interruptions because of conductor clashing due to snow or ice shedding or to wind are eliminated. Similarly, phase-to-phase or phase-to-earth faults due to trees or other objects falling across the line are avoided. The number of faults on the covered conductor lines are reported to be less than one fault per 100km per year compared to over four faults per 100km per year for bare conductor lines. Overall capitalised costs of installation, maintenance and outages (including the losses suffered by the customers) is claimed to be up to 30% lower when compared to bare conductor lines or even bundle conductor. The use of covered conductors allows them to be placed closer together, thus reducing the space required for the line.

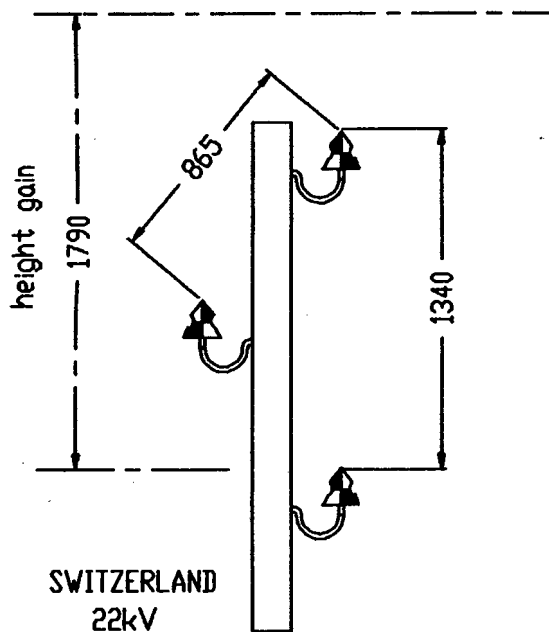
The German structure (Brandt, et al., 1989) shows a horizontal steel crossarm structure fixed over the top of the pole. The structure referred to was a prototype structure used in tests so does not necessarily represent standard practice. It is of interest, however, because of its construction, which is a steel crossarm mounted on a bracket above the top of the pole. Dimensions typical of 22kV construction have been used in the drawing. It was stated that the horizontal configuration associated with a long span is preferred because of environmental considerations. The horizontal configuration (above the top of the pole in this case) gives the best ground clearance, and hence fewer poles are used per kilometre because of the longer spans possible.



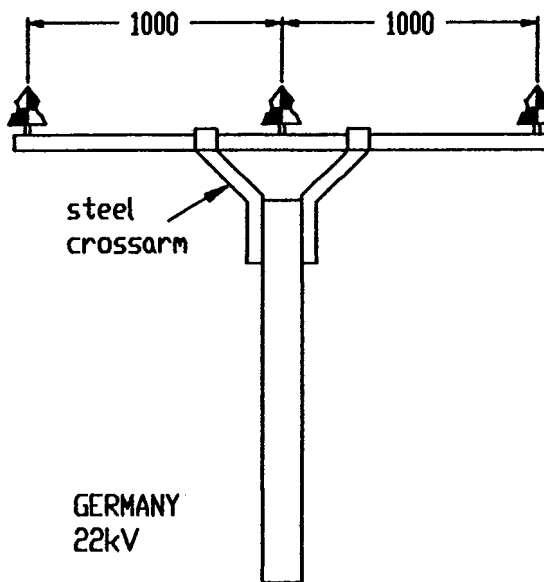
FINLAND
20kV
covered conductor



SWEDEN
24kV
covered conductor



SWITZERLAND
22kV



GERMANY
22kV

(sources are quoted in the text)

INTERMEDIATE STRUCTURES
EUROPEAN DESIGNS

FIGURE 2.24

Figures 2.25 to 2.27 show ten Australian designs which illustrate even more solutions to the basic problem of keeping three conductors at the top of a pole. All the three-phase designs shown have one factor in common: they all use crossarms of standard cross-sections. Wooden crossarms are machined to a (regional) standard size and steel crossarms are made from channel or other standard sections.

Figure 2.25 shows two configuration designs from Western Australia and two from Victoria (in the south-east).

(A): A hollow square section steel tube for the crossarm, with horizontal insulators at the ends. Details are not shown on this drawing but the crossarm assembly is complex. The top of the pole is covered by a weathershed (underneath the crossarm) and access to the spindle bolts is provided through a covered hatch at each end. The brackets which secure the crossarm to the pole are slotted to cater for poles of different diameters. (State Electricity Commission of Victoria - SECV)

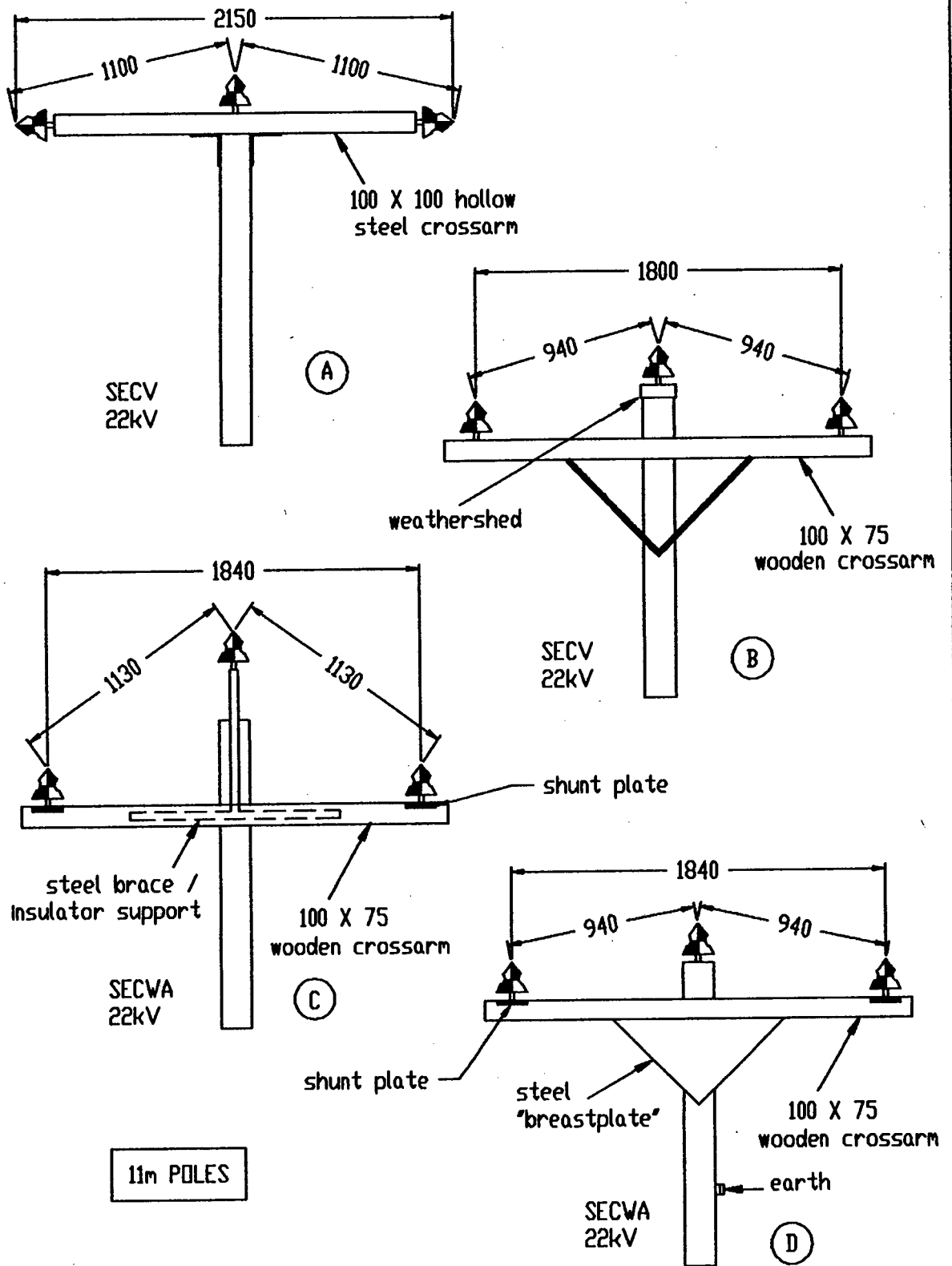
(B): The pole is capped with a weather shed through which the top spindle is fitted (SECV).

(C): The crossarm is bolted to the pole through an inverted-T raiser, which also acts as a brace. The spindle for the middle insulator is an extension of the vertical of the raiser. (State Electricity Commission of Western Australia - SECWA)

(D): The crossarm is bolted to the pole through a steel "breastplate", which also acts as a brace. (SECWA)

The outer spindles of both the (C) and (D) designs in Figure 2.25 have "shunt plates" under them. These "shunt plates" or "gang nails" are provided to distribute the leakage currents. Without the "shunt plates" the leakage currents are concentrated causing heating and sometimes fires on wooden structures.

The (B) and (C) configuration designs shown in Figure 2.26 also both have "shunt plates" fitted under the outer spindles. (The information regarding "shunt plates" was received from B. Kent in Darwin in reply to a query (Kent, 1990).)



(SEC V, 1987)
 (SEC WA, 1990)

INTERMEDIATE STRUCTURES

AUSTRALIAN PRACTICE

FIGURE 2.25

Figure 2.26 illustrates the structures used by the Power and Water Authority of the Northern Territories (PAWA). They use only fabricated steel poles and not woodpoles. This is very much the exception to the general rule. The reasons given (Kent, 1990) are that there is a lack of suitable, locally-available timber and that wood is particularly vulnerable to attack from termites.

(A): Crossarms and load-bearing components of steel are welded onto the pole and not bolted.

(B) & (C): Rectangular or square wooden crossarms are gangnailed on top (under the insulator spindle) in order to distribute leakage current.

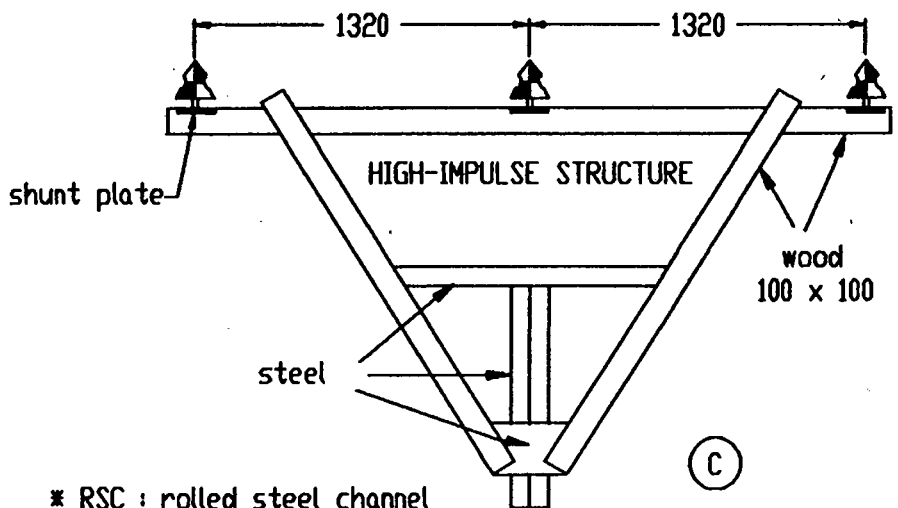
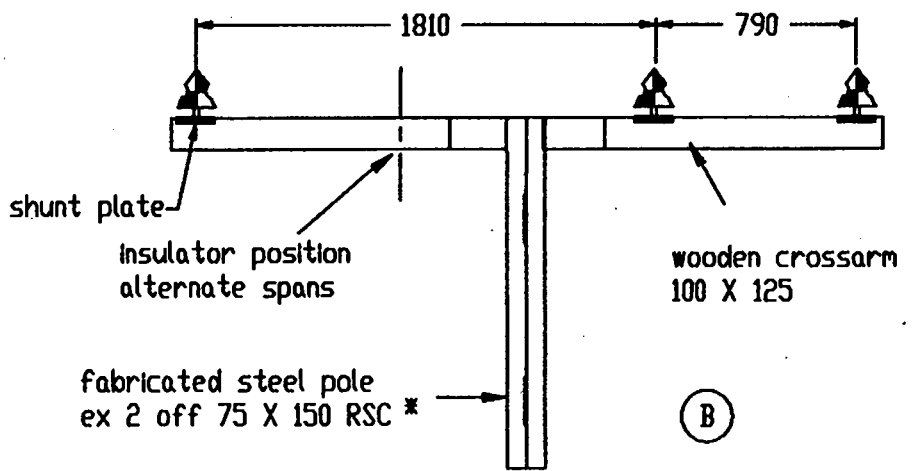
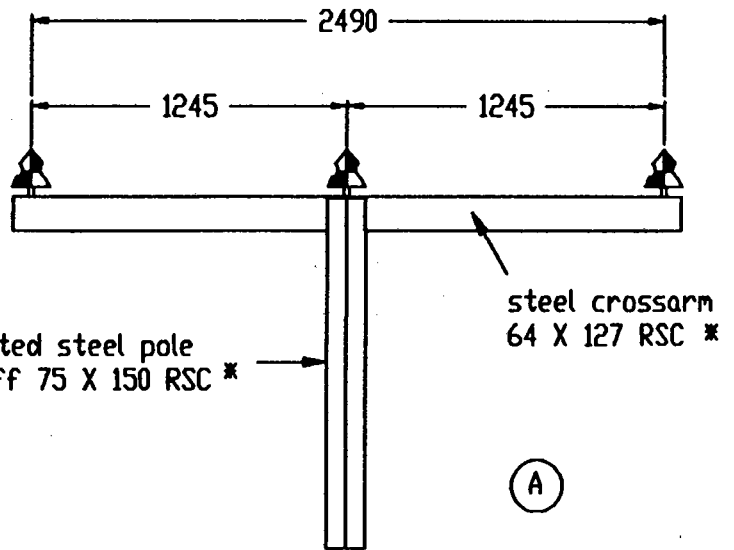
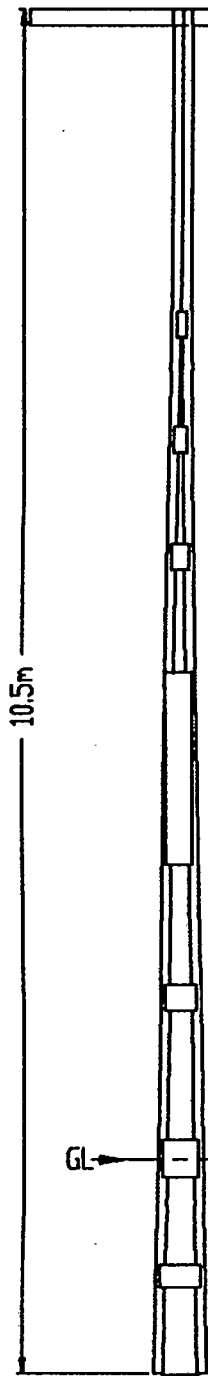
(B): The middle insulator is far to one side, in a similar fashion to Brazilian practice (Figure 2.22), again for no apparent reason.

(C): The high impulse structure uses a wooden extension structure to the steel pole in order to provide a basic insulation level (BIL) of the same order (300kV) as South African practice.

The Australian Capital Territory Electrical Authority (ACTEA, 1984) uses 12,5m concrete poles with a 2m setting depth. (The crossarm structure is not illustrated but is similar to the SECV wooden crossarm design.)

All wooden crossarm designs from the three major Australian supply authorities (SECV, SECWA, PAWA) from whom information was received, show transverse bolts at the ends of the crossarms in order to stop splitting. South African practice is to bind the pole top with several turns of galvanised wire for the same reason. The ends of wooden crossarms are not always bound, although it is standard practice to do so.

typical all-steel pole



(PAWA, 1989)

* RSC : rolled steel channel

INTERMEDIATE STRUCTURES

AUSTRALIAN PRACTICE

FIGURE 2.26

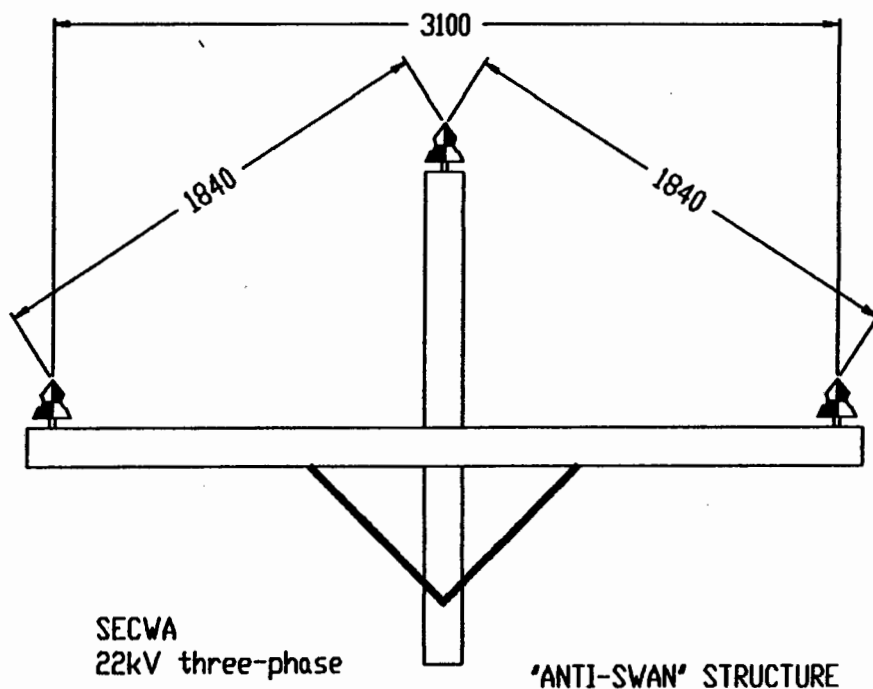
Figure 2.27 shows three Australian designs which are unusual in that they are of the few designs seen that specifically take wild-life into account:

(A): The "anti-swan" structure as used in Western Australia. Room is given for the swan to perch by lengthening the crossarm and increasing the conductor separation considerably (by about 60%). (SECWA)

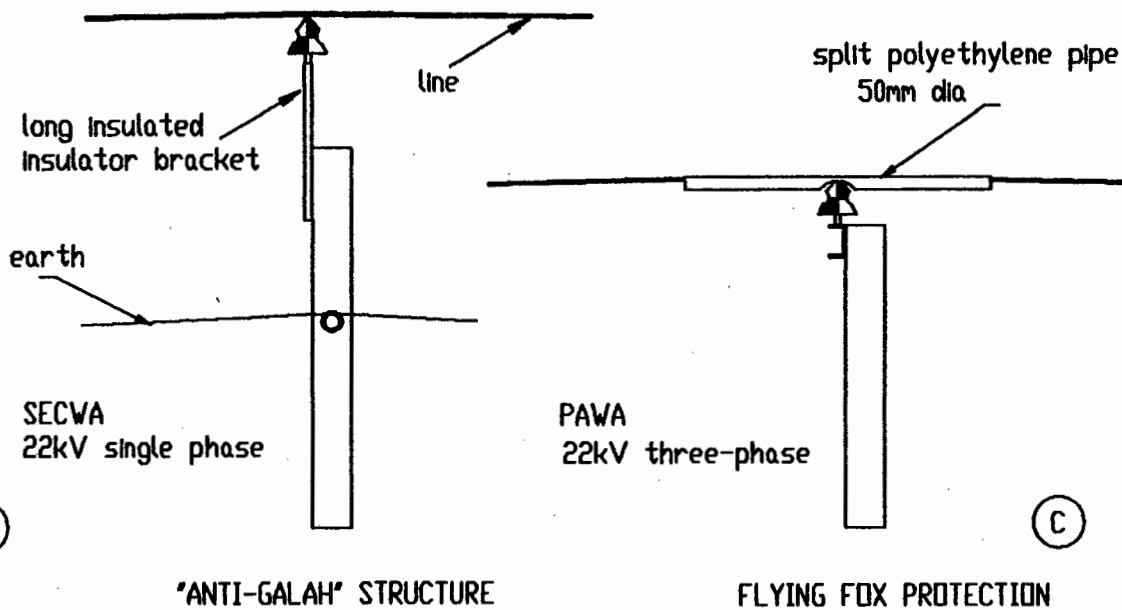
(B): This "anti-galah" structure raises the top insulator and conductor above the top of the pole on an insulated extension for single phase construction; for three phase construction they may presumably perch on the crossarm in safety. (A galah is an Australian cockatoo.) (SECWA)

(C): Flying foxes (the largest bat, with a wing-span of up to 1,5m) are prevented from coming into contact with the live conductors by covering the insulator and 600mm of conductor on either side with a (split) polyethylene pipe. The structure, being of steel, is fully earthed and the probable contact would be between a phase and earth. (PAWA)

One of the main items of interest to emerge from the data accompanying the various designs mentioned above is that many countries include a "standard" of an 11m woodpole with a top diameter of about 160mm and a ground-level diameter of about 210mm. (This pole size is also the virtual South African standard.) Foundation depth is between 1,7m and 2m. The associated span length is of the order of 100m. The current (1991) trend in South Africa is to use the longest spans possible within the design limits and terrain restrictions, that is to push the designs to the (safe) limits.



(A)



(B)

(C)

(SECWA, 1990)
(PAWA, 1989)

SPECIAL STRUCTURES FOR WILDLIFE
AUSTRALIAN PRACTICE

FIGURE 2.27

CHAPTER 3

AN EVALUATION OF LINE DESIGN THEORY

This chapter discusses and evaluates the theory of the design of 11kV and 22kV rural distribution lines using single-pole structures. It is divided into nine sections.

Section 3.1 presents a brief review of, and comment on, the literature sources used in the research.

Section 3.2 outlines and discusses a simplified procedure that could be followed when a rural distribution line is designed. The procedure is intended as a framework on which to hang the various aspects of the design theory. It shows the interrelation of those aspects. The detail of the procedure differs from organisation to organisation, depending on such factors as staffing, information and local practice.

Each of the remaining sections evaluates and compares the theories relating to a specific aspect of line design. The seven parameters or factors which have to be considered in the design of a rural line are each treated separately. There are five design parameters which are functions of the geometric configurations of the poletop structures used for the line. The two environmental factors which have to be taken into account, lightning and environmental impact, have a modifying effect on the geometric configurations.

Section 3.3 details how the sag of the conductor is calculated. Design parameters used in the calculations include the span, tension and temperature of the conductor and the wind pressure on the conductor.

Section 3.4 examines the calculations that are made to determine the load to which the pole is subjected. Only the load due to transverse wind pressure on the conductors, structure and pole is considered. The vertical load on the pole, and hence on the bottom of the foundation, is not discussed as it will not vary significantly for different poletop configurations. The formula for calculating the fibre stress in the pole, resulting from the transverse wind load, is given. Finally, the limiting and test values for this fibre stress in different species of timber are discussed.

Section 3.5 discusses the design rules for the foundations of single pole structures. General information about soil and typical values of its bearing capacity are given as a necessary background. Theories which have been in use for many years are presented and compared to other theories extracted from recently published papers on the subject.

In Section 3.6 five formulae for calculating the minimum spacing of the conductors at their point of attachment are evaluated and compared. Their derivations are dependent partly on theory and partly on experience. The galloping of conductors due to wind-induced forces is discussed in the final Part of this Section.

Section 3.7 gives a broad overview of the effect of lightning on the performance of a rural woodpole line. The different insulation levels used (the extent to which structures and components are earthed or bonded) and how these affect the lightning-related performance of the line are discussed.

Section 3.8 examines the effect that the geometry of the poletop structure may have on the electrical losses of the line. Formulae and data for use in Chapter 4, where the selected configurations are analysed, are presented.

Section 3.9 discusses in broad terms the effect that rural distribution structures have on the environment in general and on raptors in particular.

3.1 AN ASSESSMENT OF THE LITERATURE SURVEYED

The literature survey was aimed at obtaining two sets of information. It had firstly to be established whether results of similar research had been published and what those results were. Secondly, information about the different factors in the design process (as detailed in the introduction above) had to be obtained. Only some 22 published papers which covered these specific aspects of rural line design were found during the literature search. Most of these papers contained information that reflected current theories and practices on the subject of rural line design.

Textbooks, such as those by Gracey (1963) and McCombe & Haigh (1966), cover designs for the full range of line voltages. References such as these are important as they include theory and formulae still being used in South Africa.

Eskom was a major source of information, in addition to the design drawings obtained from the Eskom Regions. Information obtained from Eskom Design Guides or from personal contacts proved to be of great value in evaluation of the poletop configurations or design theories.

Standards issued by authorities such as the South African Bureau of Standards were important for specific aspects of the research, such as pole strengths.

During the this literature survey four "codes of practice" were obtained and used as references. These were from South Africa (SAIEE, 1966), Britain (BS1320, 1947 and ESI, 1974), USA (REA, 1982 and REA, 1988) and Australia (ESAA, 1990). These codes of practice differ very widely in their complexity and content.

The complete REA Code is probably the most detailed and exhaustive if taken to its ultimate cross-references. It refers to the National Electrical Safety Code (NESC, 1987) and other guides. The REA publications (eleven are listed in REA (1982)) include those covering details of all structures and design and construction guides. Design information is currently in both imperial and metric units.

The British Electricity Supply Industry standard documentation (ESI, 1974) is more detailed than the old BS1320 (1947). The information has also been metricated. Information on the subject of 11kV and 22kV line design is however spread across several publications.

The Australian design and maintenance guidelines (ESAA, 1990) give a good background to the subject. They provide theoretical information (for example on catenaries and sags), information on materials used in the construction of the lines (for example woodpoles and conductors), and information on clearances from conductor to structures, ground, etc. The guideline does not give details of any structures or designs. The individual supply commissions produce their own detailed design manuals (for example SECV (1987), SECWA (1990), PAWA (1989)) for their own specific climatic or structural requirements.

The South African Code of Practice (SAIEE, 1966) is currently being revised. It is still in imperial units and incomplete compared to the Australian Guidelines. Eskom has, however, issued a two-volume publication (Eskom, 1989a) which presents aspects of the design of rural distribution lines. This publication is detailed and extensive yet incomplete because it does not include all the Eskom rural distribution structures. The A-frame used by Western and Southern Cape Regions is omitted. The structures and construction methods used in the publication will be superseded by the new national Eskom standards currently under development.

3.2 A SIMPLIFIED DESIGN PROCEDURE FOR A RURAL LINE

This section explains a simplified procedure which could be used for the design of the line, or more correctly, for the design of one (representative) span.

The activities leading up to and including the design of a rural line are outlined as follows:

A. CUSTOMER REQUIREMENTS

The request for the construction of a rural line may come from a number of sources. Typically, a group of farmers get together and approach the local Power Marketing Department of Eskom. The requirements from the farmers for the size (kVA), location and use (for example, domestic, farm workshops or irrigation pumps) of their individual supply points are obtained by the Power Marketing Department. This information forms the basis for the request from the customer(s) for the supply of electricity.

B. SURVEY OF THE LINE ROUTE

The data regarding the locations of the requested supply points is passed on to the Survey Section with the request that a suitable route for the line be obtained. The land surveyor goes into the field and evaluates alternative routes for the line. As part of this evaluation he has to negotiate with the land-owners for a suitable route. Once the route has been finalised legal wayleaves for the line to pass over the properties are registered. The route that the line will follow is essentially specified by the location of "bendpoints" which are primarily determined by details of the terrain (topography, water courses, farmed land, fences, roads, railways, telephone lines, power lines, etc). The surveyor then obtains a "profile" (the variations in ground level) of the terrain along the line route. The soil conditions along the route are assessed in order to establish the soil type and bearing capacity for the foundation design.

C. DESIGN OF THE LINE

The designer has standard designs of structures and guidelines for the design and construction of rural lines available. (The sources for design data and criteria are given in the previous Section and are examined in detail in following Sections.) The line voltage and the conductor size and type are provided by the System Expansion Planning Section and depend on the load to be supplied to the customer (as obtained by Marketing). The other information available to and needed by the designer includes design data on conductors (size, tensile strength, rated current, etc), poles (timber species, permissible stress, length, top diameter, etc) and poletop structures (hardware, insulators, etc). The items used for the construction of the line are also be listed in a stores database from which availability and cost can be ascertained.

The designer starts the design of the line by setting out, in collaboration with the Survey Section, the initial positions of the intermediate poles between the bend points. The initial span lengths used to fix these initial positions are calculated by dividing the distance between bend points (a strain section) into parts which are approximately equal to the limiting design span for the particular poletop configuration. As an example, a line using a configuration with a limiting design span of (say) 130m could have nine spans of 124m in a strain section which is 1 116m long. The actual positions of the intermediate poles are functions of both the limiting (maximum) design span for the line and the line profile and terrain detail. The process of optimising the design of the line can be started once the initial representative span for the particular strain section has been chosen.

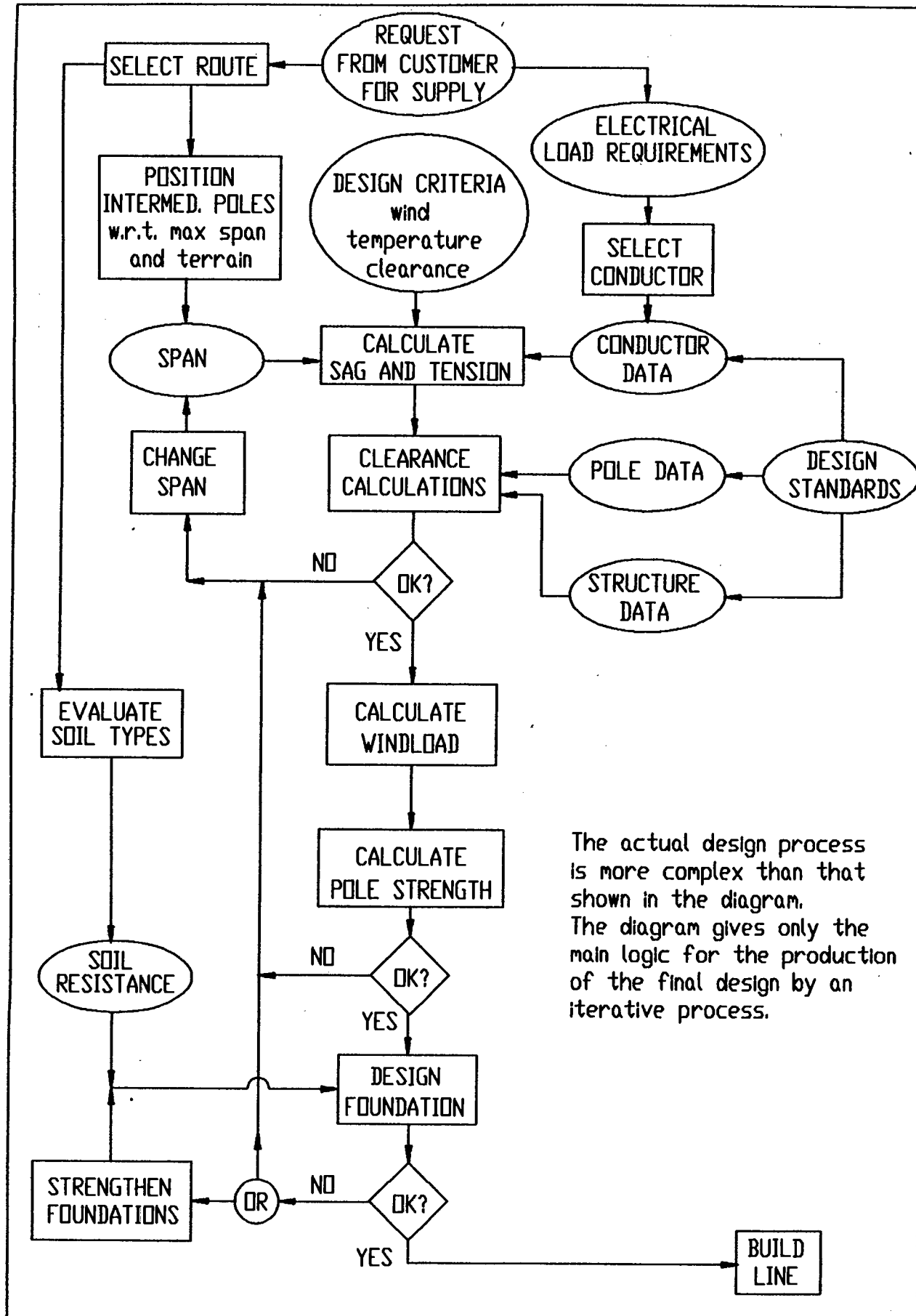
The limits given by the design parameters (obtained from the design guidelines or standards) are checked at each stage and the design procedure repeated and the span adjusted so that these limits are not exceeded. The process should optimise the design so that the best economic design is produced and the line is not overdesigned. This phase of the overall design is essentially that of mechanical design, involving tension, stress, soil bearing capacity, overturning moments, etc. The electrical design of the line was completed by the specification of its voltage and the current-carrying capacity (conductor size).

The simplified design procedure followed in this thesis assumes that the route over which the line is to be built is completely level and the calculations are based on the design of one (representative) span.

The designer has to perform three sets of calculations:

- The sag and tension of the conductor and hence the ground clearance have to be calculated (Section 3.3).
- The stress in the pole produced by the imposed wind forces have to be calculated (Section 3.4).
- The capability of the foundation to resist the overturning of the pole must be calculated (Section 3.5).

Figure 3.01 sets out the logic of the design procedure. Once the first choice of the position of the intermediate poles (and hence the length of the representative span) is made then the sag and tension calculations can be done. The design criteria for wind, temperature and clearance are known from environmental and statutory publications and the design standards provide data about the conductor, pole and structure. The calculation of the load imposed on the structure by the wind enables both the stress in the pole and the size of the foundation to be calculated. This flow-charted procedure shows (in this simplified case) that the main option that the designer has, if design limits are exceeded, is to change the span and then to repeat the relevant calculations. The aim of the designer is to provide the most economic design for the line. This optimum design, which is "OK" on the flowchart, will probably use the longest spans possible within the design constraints imposed by statute, conductor parameters, pole strength, foundation strength and cost considerations.



The actual design process is more complex than that shown in the diagram. The diagram gives only the main logic for the production of the final design by an iterative process.

SIMPLIFIED PROCESS DIAGRAM FOR THE DESIGN OF A REPRESENTATIVE SPAN OF A RURAL DISTRIBUTION LINE

FIGURE 3.01

3.3 DESIGN OF THE LINE WITH RESPECT TO SPANS, SAGS AND TENSIONS

This Section is divided into three Parts, each of which covers a particular aspect of the subject-matter. Part 3.3.1 sets out the legal and Code of Practice design parameters for conductors in an overhead line. Part 3.3.2 presents and explains the basic formulae used for the calculation of sag. Part 3.3.3 analyses the effect of a change in temperature on the tension and sag of a conductor. Each formula presented is illustrated by means of a worked example.

3.3.1 DESIGN PARAMETERS FOR SOUTH AFRICAN CONDITIONS

The Electrical Machinery Regulations of the Machinery and Occupational Safety Act (MOS Act, 1983) and the SAIEE Code of Practice (1966) lay down the following design parameters for the design of overhead distribution lines.

Clearances, from the conductor to ground, depend on the sag of the conductor and are normally determined for a maximum conductor temperature of 50°C. The minimum conductor-to-ground clearance for 11kV is given as 5,1m and for 22kV is given as 5,2m. (Regulation 15, MOS Act (1983))

The line should be designed to withstand the combined effects of a minimum temperature of -5°C and a maximum wind pressure of 700Pa on 0,6 of the projected area of the conductors without the tension exceeding 40% (safety factor of 2,5) of the rated ultimate tensile strength of the conductor. (Regulation 18, MOS Act (1983))

SAIEE (1966) recommends that in the case of a rural 11kV or 22kV line, where span lengths do not usually exceed 160m, that the initial tension of the conductor (that is, the tension during stringing and under the then prevailing conditions) be limited to a specific value. This specific value is required to be such that the tension in the (ACSR) conductor after stringing does not exceed 25% of the ultimate tensile strength at a temperature of -5°C under "no-wind" conditions. The earth wires are normally strung to match conductor sag. In which case,

tensions as recommended in the Code for the earth wire are generally not exceeded. (Paragraph 3.2.2, SAIEE Code of Practice (1966))

Creep, the inelastic extension of the conductor over time, is allowed for by designing the line so that the initial clearances are greater than the required limits. This is done by using the "initial" value for Young's modulus in the calculations. As an example, the initial tension is 4kN and the sag 1,8m for a 150m span. The sag will increase by 0,2m due to creep over time. Adequate clearances are therefore maintained throughout the life of the line.

3.3.2 BASIC FORMULAE FOR THE CALCULATION OF SAG

The conductor takes the shape of a catenary when strung between two supports at the same level. Many sources (for example: Nolasco (1989), Gracey (1963), SAIEE (1966), Eskom (1989)) use similar formulae, with differing symbols, for the calculation of sag in the line. They are based on the equation for the catenary. The catenary equation is based on the expansion series for the hyperbolic cosine. Figure 3.02 defines some of the symbols and terms used in the formulae given below.

The catenary equation for sag is given by Gracey (1963) (with symbols changed and metricated):

$$s = w_c l^2 / 8H + (w_c / 6H)(w_c l^2 / 8H)^2 + 0,4(w_c / 6H)^2 (w_c l^2 / 8H)^3 \quad \text{Equation 3.1}$$

where:

s is the sag (m)

w_c is the unit weight of the conductor (N/m)

l is the span (m)

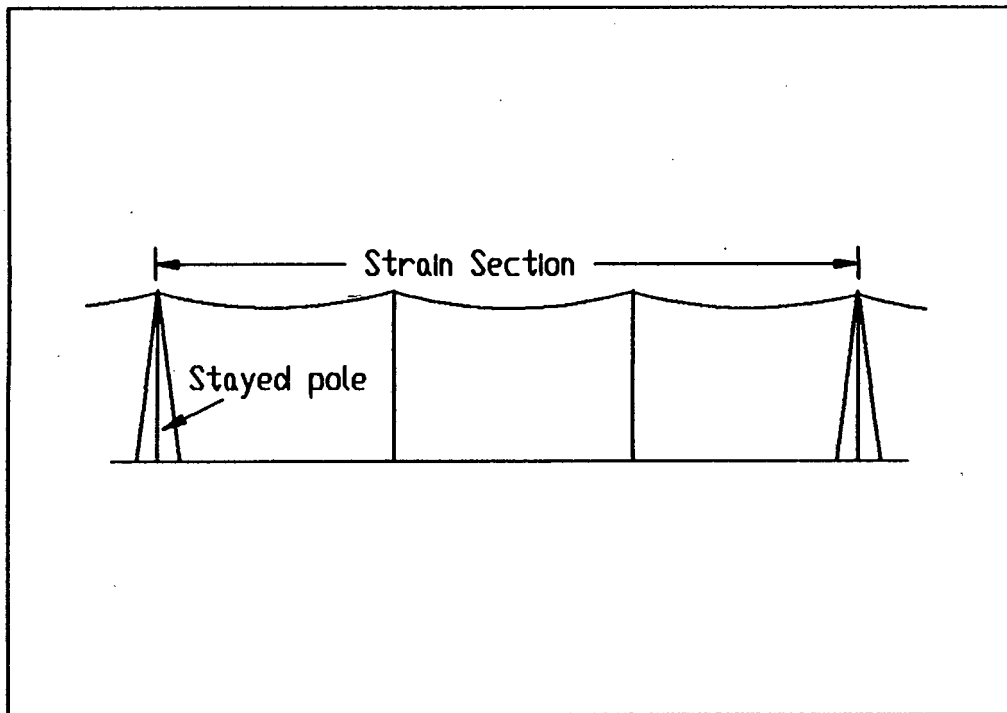
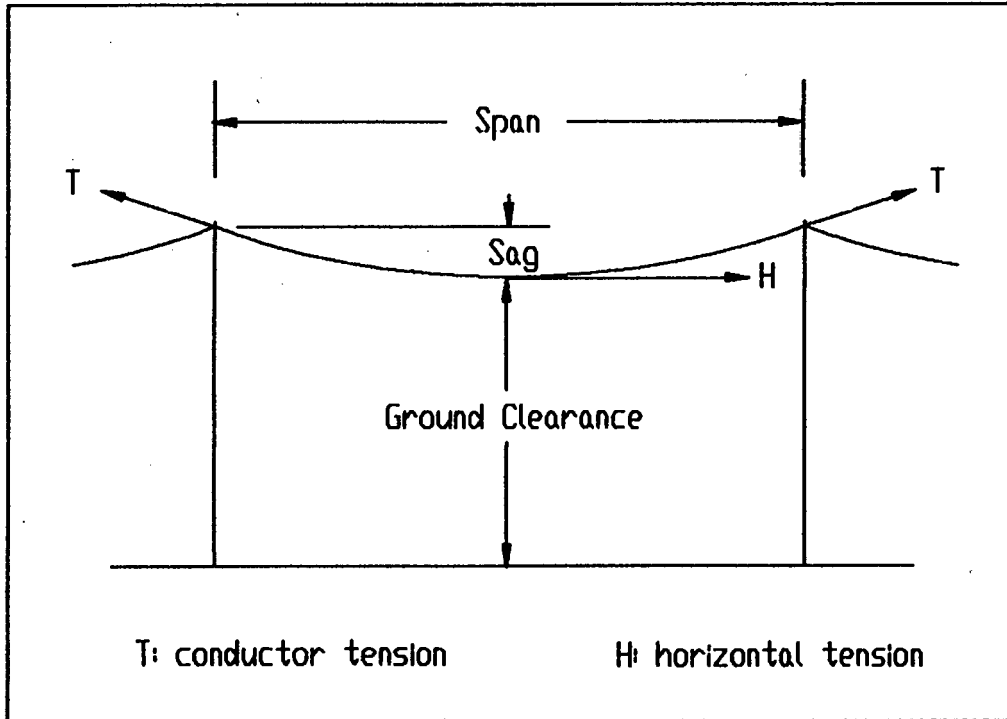
H is the horizontal tension (N)

The parabolic equation is an approximation for the catenary equation, being the first term of the expansion series. Its advantage is that it is simpler to use for calculating the sag. The difference in calculated sag between the two equations is less than 0,5% for sags of up to about 5% of the span.

The parabolic equation is given by (Gracey, 1963):

$$s = w_c l^2 / 8H \quad \text{Equation 3.2}$$

The symbols have the same meaning as for the catenary equation.



LINE DESIGN: DEFINITION OF TERMS

FIGURE 3.02

Example: Comparison of Catenary and Parabolic Sags

(The example uses a sag of 5%, which is not usual for a 22kV line, in order to check the error given above. The maximum permissible sag, in order to provide a 5,2m ground clearance for a 22kV line with a 9m attachment height would be of the order of 3,8m. This is a sag of 1,9% for a 200m span.)

$$\text{span } (l) = 200\text{m}$$

$$\text{horizontal tension } (H) = 1 \cdot 264\text{N}$$

$$\text{conductor unit weight } (w_c) = 0,257\text{kg/m} = 2,52\text{N/m} \quad (\text{Mink})$$

$$\text{sag (catenary)} = 10,001\text{m} \quad (\text{Equation 3.1})$$

$$\text{sag (parabolic)} = 9,968\text{m} \quad (\text{Equation 3.2})$$

$$\text{sag \% (catenary)} = 10,001 \times 100/200 = 5,0\% \text{ of the span.}$$

$$\text{error due use of parabolic equation} = (10,001 - 9,968) \times 100 / 10,001 = 0,33\%$$

3.3.3 CALCULATION OF CONDUCTOR TENSIONS AND SAGS FOR DIFFERENT CONDITIONS

The calculation of the sag of the conductor for a given span requires only that the tension of the conductor at the centre of the span and the unit conductor weight be known (Equation 3.1). This would be sufficient if the conditions under which the conductor was used did not change, that is, if the temperature and the effective conductor weight remained constant. However, a decrease in temperature or an increase in the effective weight (because of wind blowing across the line or ice accretion) would cause an increase in tension that may cause the conductor to fail.

The Code of Practice (SAIEE, 1966), as mentioned previously, requires that the initial tension in a conductor should be such that the tension under (different) conditions of no wind and at a temperature of -5°C should not exceed 25% of its ultimate strength. This data for tension, wind load and temperature provide a set of reference values that enable the tension (and hence the sag) to be calculated for any other conditions of wind load or temperature.

The equation that makes it possible to calculate the value for the conductor tension under different conditions of wind load or temperature is the "equation of change of state" (Nolasco, 1989) given below.

$$l^2((w_1/H_1)^2 - (w_2/H_2)^2)/24 - e(t_1 - t_2) - (H_1 - H_2)/EA = 0 \quad \text{Equation 3.3}$$

where:

l is the span (metres)

w_1 and w_2 are the resultant loads (N/m) (see Note)

H_1 and H_2 are the horizontal tensions (N)

e is the coefficient of expansion ($^{\circ}\text{C}^{-1}$)

t_1 and t_2 are the temperatures ($^{\circ}\text{C}$)

E is Young's modulus (N/mm^2)

A is the cross-section area of the conductor (mm^2)

and: suffix "1" refers to the reference state, suffix "2" refers to the "new" state

Note: Wind load on the conductor can be considered to be an additional load acting transversely on the conductor at right angles to the weight load. The resultant of these loads is taken into account in the calculations as follows: (The suffix has been omitted as the equation is valid for either state.)

$$w = (w_c^2 + w_w^2)^{0.5} \qquad \text{Equation 3.4}$$

where:

w is the resultant load (N/m)

w_c is the conductor unit weight (N/m)

w_w is the conductor unit wind load (= P_wd_ck) (N/m)

and P_w is the wind pressure (Pa)

d_c is the conductor diameter (m)

k is a shape factor (= 0,6 in SAIEE (1966))

Gracey (1963) also uses a similar formula (with different symbols) for determining the tension resulting from a "variation in temperature".

Example:

A Mink conductor with a span of 150m is to be strung at a temperature of 25°C. The construction crew need to know to what tension it should be strung if the wind is blowing across the line at a pressure of 250Pa during the stringing operation. The tension at -5°C and 700Pa wind pressure and the maximum sag at 50°C and no wind are also required in order to check compliance with the MOS Act (1983).

Mink conductor data: (manufacturer's data)

conductor unit weight (w_c) = 2,52N/m

conductor diameter (d_c) = 0,01098m

conductor area (A) = 73,65 mm²

Young's modulus (E) (initial) = 49 100N/mm² (final) = 80 400N/mm²

coefficient of expansion (e) = 19,31 X 10⁻⁶ /°C

ultimate tensile strength (UTS) = 21 900N

Note: Young's modulus: The "initial" value is used for the calculation of stringing tension so that when the line has been in use for about ten years the necessary sag-related clearances are still maintained. The creep, or inelastic extension, of the conductor is compensated for in this way. The "final" value is used for the calculation of conditions such as the maximum tension and sag when the line has been in use for about ten years, by which time the conductor has reached its maximum extension due to creep.

Reference conditions: (Code of Practice (SAIEE, 1966))

tension (H_1): 25% of ultimate strength = 5 475N

temperature (t_1) = -5°C

there is no wind so that $w_1 = w_c = 2,52\text{N/m}$

Data for Calculation A - Stringing conditions:

wind pressure (P_w) = 250Pa (30km/h wind)

shape factor (k) = 0,6

unit wind load (w_w) = $250 \times 0,01098 \times 0,6 = 1,65\text{N/m}$

resultant load (w_2) = $(2,52^2 + 1,65^2)^{0,5} = 3,01\text{N/m}$ (from Equation 3.4)

stringing temperature (t_2) = 25°C

Data for Calculations B and C - MOS Act compliance:

(B):

limit of 40% of UTS (8 760N) at a temperature (t_2) of -5°C and a wind pressure (P_w) of 700Pa.

resultant load (w_2) = $(2,52^2 + 4,61^2)^{0,5} = 5,25\text{N/m}$ (from Equation 3.4)

(C):

sag at a temperature (t_2) of 50°C under conditions of no wind ($w_2 = w_c = 2,52\text{N/m}$).

Answers:

The required tensions (H_2) for calculations A and B are obtained by successive approximations to solve Equation 3.3.

(A): stringing tension (H_2) = 4 313N (using the "initial" Young's modulus)

(B): "worst case" tension under MOS Act conditions = 7 231N

(using the "final" Young's modulus)

This is less than the limit (8 760N) and therefore meets the statutory requirements.

The sag for a "no wind" condition at 50°C is obtained from Equation 3.1.

(C): "worst case" sag under MOS Act conditions = 2,59m

(The tension was calculated to be 2 731N from Eqn. 3.3)

The clearances between the (lowest) conductor and the profile of the ground under the line must be checked once the sag for the span has been calculated. The sag is subtracted from the attachment height of the lowest conductor to give the clearance to the ground in the simple case of two structures of equal height on level ground. For a typical lowest conductor attachment height of 8,87m the clearance is $8,87 - 2,59 = 6,28\text{m}$. This meets the statutory requirements for both 11kV (5,1m) and 22kV (5,2m).

Sag templates are still used to do checking of clearances over uneven ground profiles (although computer programmes to do profiles and clearances are becoming more freely available). Sag templates are cut from thin transparent plastic and represent, to scale, the curve that the chosen conductor follows when suspended from the line structures at a specific tension.

The sag templates are used to check conductor-to-ground clearance and hence also to check line structure pole positions. The pole position would have to be moved, or the pole lengthened, should the clearance be inadequate.

3.4 RESISTANCE OF INTERMEDIATE POLES TO BENDING FORCES CAUSED BY WIND LOAD ON THE CONDUCTORS AND STRUCTURE

Under windless conditions no significant unbalanced horizontal forces or moments act on an intermediate pole in a rural distribution line. The forces in the length of the line are balanced as the tensions to either side of the pole are equal and opposite.

Wind pressure acts on the exposed surfaces of the conductors, structure and pole when the wind blows transversely across the line. The wind load on each of these three parts of the total structure can best be calculated separately and hence also the bending moments caused by the wind load.

Conductors:

The transverse wind load on the pole caused by the conductors is calculated by using the "wind span". The wind span for a particular pole is the sum of the adjacent half-spans. The resulting total force on the conductors acts at the centre of wind action of the conductor configuration.

Structure and pole:

The total force acting on the poletop structure or pole is directly proportional to the exposed area and acts at the centre of wind action of the area.

The arms of the bending moments applied to the pole by these forces are their respective distances from the centres of wind action to ground level. The total bending moment applied to the pole is the sum of these three bending moments.

The magnitude of this applied bending moment is needed in order to calculate the stresses set up in the pole (discussed in this Section) and also to design the foundation for the pole (discussed in Section 3.5).

This Section is divided into five Parts. The first two Parts discuss the different approaches of the South African Code of Practice (SAIEE, 1966) and of the Rural Electrification Administration of the USA (REA, 1982) to the calculation of wind load. The third Part compares the use of safety factors and shape factors in the calculation of wind loads as used by the above two Code and by others. The fourth Part sets out and explains the formulae for calculating the stress in the pole. The last Part discusses the values used for the fibre stress in a pole. It also presents data from different sources for different species of timber.

3.4.1 WIND LOAD CALCULATIONS:
SOUTH AFRICAN CODE OF PRACTICE

The formulae given have been derived (metricated and symbols changed) from the Code of Practice (SAIEE, 1966).

The force acting on each conductor is given by:

$$F_c = k_c P_w d_c l_w \quad \text{Equation 3.7}$$

The force acting on the pole is given by:

$$F_p = k_p P_w A_p \quad \text{Equation 3.8}$$

The force acting on the structure mounted on the pole is given by:

$$F_s = k_s P_w A_s \quad \text{Equation 3.9}$$

where:

F_c , F_p and F_s are the transverse loads (N)

k_c , k_p , k_s are a shape factors

(0,6 for a cylinder and 1 for a flat surface)

P_w is the wind pressure (Pa)

d_c is the conductor diameter (m)

l_w is the wind span (m)

A_p is the projected area of the pole (m²)

A_s is the projected area of the structure (m²)

The Code (SAIEE, 1966) does not take these formulae any further. It is left to the user of the Code to develop the application.

3.4.2 WIND LOAD CALCULATIONS:

RURAL ELECTRIFICATION ADMINISTRATION, USA

The National Electrical Safety Code gives detailed rules (NESC, 1987) for the design of woodpole structures. The mechanical design manual of the REA (REA, 1982) is based on these rules and sets out the design procedures. The design loads to be supported by the structure are multiplied by given overload capacity factors (safety factors) in order to obtain the forces which the structure has to withstand. The ground-line resisting moment is calculated from these forces and compared to the actual resisting moment of the different classes of poles (as detailed in ANSI 05.1 (Specifications and Dimensions for Wood Poles)). The pole class which just meets or exceeds the required moment is selected.

The resisting moment (or moment of resistance) of the pole is the resistance that the pole has to the bending moment caused by the (wind-imposed) forces acting on the conductors, structure and pole.

For an intermediate pole (unguyed, zero deviation angle) the required resisting moment of the pole is given by (based on the formula given in REA (1982)):

$$M_r = l_w k_s (w_1 h_1 + w_2 h_2 + w_3 h_3) + k_s P_w (2d_t + d_g) h_p^2 / 6 \quad \text{Equation 3.10}$$

where:

M_r is the resisting moment (Nm)

l_w is the horizontal wind span (m)

k_s is the overload capacity factor (safety factor)

w_1, w_2, w_3 are the wind loads per metre (N/m) (of each conductor)

h_1, h_2, h_3 are the attachment heights (m) (of the conductors above ground level)

P_w is the wind pressure on the pole (Pa)

d_t, d_g are the pole diameters (m) (at top and ground level)

h_p is the height of the pole above ground level (m)

Other items mounted on the top of the pole, which may cause significant additional wind load, should also be included in the calculation.

The formula used by the REA (Equation 3.10) is complete in that it includes safety factors and the heights of application of the forces. The data can be entered directly in the equation in order to obtain the result. NESC (1987) uses shape factors for wind loads of 1 for a cylinder and 1,6 for a flat surface. These factors are included in the values provided (REA, 1982) for the wind pressure in the design data for the conductors used in the calculations. The horizontal wind pressure for "general loading" ("light loading districts") and ice-free conductors is given as 430Pa (REA, 1982).

3.4.3 COMPARISONS OF FACTORS APPLICABLE TO THE CALCULATIONS

At first sight the calculation of the total imposed moment caused by wind blowing transversely across a rural distribution line would appear to be straightforward. The basic mathematical relation is simple:

$$\text{moment} = (\text{force} / \text{unit area}) \times \text{area} \times \text{height}$$

This calculation is carried out for each item which has a different distance from ground level. The individual moments are all added together to give the total imposed moment. This is the approach used by Gracey (1963).

Gracey (1963) also uses a "safety factor" but he applies it to the allowable stress (the stress is divided by the factor) and not to the load. REA (1982) states that the NESC (1977) changed the "percentage of ultimate stress" (applied to the structural members) to an "overload capacity factor" (applied to the load). This use was illustrated in Equation 3.10. Australian practice (ESAA, 1990) uses stated percentages of failing loads as "design load limits". The method of use of "safety factors" in the South African Code (SAIEE, 1966) is not specifically stated (for example by means of an equation). It is implicit in the wording that the factor could be applied to the load (multiplied) or to the stress (divided into).

There is clearly a risk in ill-informed use of formulae if the factor of safety or overload capacity factor is used incorrectly. This is a strong argument in favour of standard complete formulae as used in REA (1982).

A "safety factor" is intended to cover errors in data, calculation and manufacture. The closer the tolerances can be on these items, the lower the safety factor can be. REA (1982) uses a safety factor of 2 compared to South African practice which uses 2,7 for a similar grade of structure. The sheer volume of tests carried out and number of structures erected in the U.S.A. presupposes better statistics, enabling better, more predictable, data to be provided. It would appear that U.S.A. practice, as typified in REA (1982), uses a lower safety factor than South Africa because their data, design and construction standards are more rigid.

The basic calculations of Gracey (1963) do not use shape factors when wind loads on conductors or poles (cylindrical shapes) are calculated. Shape factors are intended to make allowance for the fact that wind will flow around a curved object and the effective pressure will be decreased as a result.

The (draft) Australian guidelines (ESAA, 1990) take shape factors into account by specifying different design wind pressures for different component shapes. The fact that the design wind pressure for the conductor is so much lower (500Pa) than that for a cylinder (750Pa) implies that the small diameter of the conductor decreases the effect of the wind even more. The design wind pressure for a flat surface is given as 1 200Pa.

The ratios between cylindrical and flat surfaces for both the ESAA (1990) and NESC (1987) are very similar to that of SAIEE (1966): 0,625, 0,625 and 0,6 respectively. The design wind pressures (wind pressures on a flat surface) for use with these derived "shape factors" are: 1200Pa, 688Pa (derived from 430Pa X 1,6 shape factor) and 700Pa respectively. These design wind pressures could be expected to be different as they are based on different climatic conditions.

Example: Calculation of Wind Load and Moments

(Based on the Code of Practice (SAIEE, 1966)).

A span of a strain section of a Mink conductor line is 150m. The wind pressure is 700Pa. The following data is given:

- conductor diameter (d_c) = 0,01098m
- pole height above ground (h) = 9,2m
- pole diameter at top (d_t) = 0,160m
- pole diameter at ground (d_g) = 0,206m
- transverse area, poletop structure (A_s) = 0,1m

(The centre of wind action of the poletop structure and the conductors is at poletop level, at 9,2m above ground.)

Shape factors (k_c , k_p , k_s) for the conductor, pole and structure are: 0,6, 0,6 and 1 respectively.

From Equation 3.7 the force acting on each conductor is:

$$F_c = 0,6 \times 700 \times 0,01098 \times 150 = 691\text{N}$$

Total force on the three conductors is thus 2 075N which acts at 9,2m above ground level.

The area of the exposed part of the pole is:

$$A_p = 9,2 \times (0,160 + 0,206)/2 = 1,684\text{m}^2$$

From Equation 3.8 the force acting on the pole is:

$$F_p = 0,6 \times 700 \times 1,684 = 707\text{N which acts at 4,3m above ground level.}$$

(See Note below)

From Equation 3.9 the force acting on the structure is:

$$F_s = 1 \times 700 \times 0,1 = 70\text{N which acts at 9,2m above ground level.}$$

Note: This distance is to the centre of wind action of the projected shape of the pole which is a trapezium. The formula used by the REA (1982) (Equation 3.10) recognises this in the relation given for the moment of the pole. South African practice, in general, is to approximate the projected shape of the pole to a rectangle, where the centre of wind action is at the centre.

The moments of the forces on the parts of the structure about ground level are:

$$\text{conductors: } 2\,075 \times 9,2 = 19\,090\text{Nm} \quad (83,8\%)$$

$$\text{pole: } 707 \times 4,3 = 3\,040\text{Nm} \quad (13,4\%)$$

$$\text{poletop structure: } 70 \times 9,2 = 644\text{Nm} \quad (2,8\%)$$

$$\text{total moment (M}_t\text{)} = 22\,774\text{Nm}$$

(This total moment (M_t) is required for the calculation of pole stress in the next Part of this Section.)

$$\text{The total force (F}_t\text{) is: } 2\,075 + 707 + 70 = 2\,852\text{N}$$

$$\text{The arm (h) of the total moment is: } 22\,774/2\,852 = 7,99\text{m}$$

(These values are required for the calculation of the foundation strength in Section 3.5.)

This example illustrates several factors which are relevant to the accuracy of the design calculations.

The effect of the pole top structure on the total moment is about 2%. Thus the effect of any error in calculating the exposed area of this structure will be negligible.

Using a rectangle for the projected area of the pole instead of a trapezium has even less effect (less than 1%).

The conductor has the greatest effect (83,8% in this example). However, the conductor diameter is accurately known and the effect of using the span instead of the true length of the conductor (catenary) causes an error of less than 0,1%. The attachment heights of the conductors have the greatest effect on the magnitude of the total moment imposed by the wind and their accurate determination is therefore important.

The above calculations are typical of those used in Chapter 4 for the analysis of South African practice.

3.4.4 CALCULATION OF THE SAFE BENDING LOAD FOR A POLE

When a pole is subjected to a cantilever load (such as the wind load on the conductors, pole and structure) it is subjected to a bending moment, the maximum of which occurs at ground level. The capability of the pole to resist the imposed bending moment is a function of its section modulus (Z) and the permissible bending stress for that pole (f_b). The permissible bending stress is calculated from the stress at failure (f_t) by applying a safety factor. The stress at failure is also known as the "modulus of rupture" and is obtained for a particular timber species from tests carried out on representative sample poles.

The section modulus of the pole is required for the calculation of the maximum bending moment that the pole can withstand without failure. This bending moment is also known as the maximum moment of resistance.

The section modulus for a solid circular pole is given by (Gracey, 1963) (metricated and with symbols changed):

$$Z = 3,14 d_g^3/32 = 0,0982 d_g^3 \quad \text{m}^3 \quad \text{Equation 3.11}$$

where d_g is the pole diameter (m) at ground level.

The maximum moment of resistance of the pole (M_p) is calculated from (Gracey, 1963) (metricated and with symbols changed):

$$M_p = f_b Z = f_b (0,0982) d_g^3 \quad \text{Nm} \quad \text{Equation 3.12}$$

where f_b is the permissible bending stress (Pa).

This maximum moment of resistance of the pole (M_p) must be greater than the total applied moment (M_t), or the pole may (theoretically) fail in use.

Example:

Calculation of Maximum Moment of Resistance of the Pole

The results and data from the previous example are used here:

factor of safety (k_s) = 2,7 (intermittently loaded pole (MOS Act, 1983)

modulus of rupture (f_t) = 84MPa (pinus radiata pole, SABS 753 (1964)

pole diameter at ground level (d_g) = 0,206m

total imposed bending moment (M_i) = 22 774Nm

permissible bending stress (f_b) = $f_t/k_s = 84/2,7 = 31$ MPa

From Equation 3.12 the maximum moment of resistance of the pole is given by:

$$M_b = 31 \times 10^6 (0,0982 \times 0,2063) = 26 611 \text{Nm}$$

the total imposed bending moment (M_i) = 22 774Nm

This means that the pole that is to be used for this structure under these conditions will not fail.

3.4.5 TEST STRESS, PERMISSIBLE STRESS AND RUPTURE STRESS IN WOODPOLES

Three different stress levels are described in the literature: test, permissible and rupture stress. Confusion often arises about what these terms mean and where which values should be used in calculations.

TEST stress is exactly what its name suggests. It is a stress which occurs in the extreme fibres of the pole when it is test-loaded as part of the production cycle. The imposed load is not intended to cause the pole to fail. The test would however eliminate (very) weak poles from the batch.

PERMISSIBLE or allowable or design stress is the stress used in the design of the structure. A safety factor is used in the calculation of the permissible stress.

RUPTURE stress is the stress in the extreme fibres of the pole when it breaks.

A. TEST STRESS

Distribution line poles are routinely tested in South Africa after manufacture in an attempt to ensure that they will not fail in service. Every pole is tested to the required test stress limit for its timber species.

Both SABS 753 (1982) (pine poles) and SABS 754 (1982) (eucalyptus poles) state that the poles, when tested in accordance with the requirements as laid down in the standard, should be capable of withstanding a certain maximum fibre stress in bending. This maximum fibre stress is given as 55MPa for pine and most eucalyptus poles and 75MPa for *E. cloeziana* and *E. paniculata*. The test stress is thus either 55MPa or 75MPa depending on the timber species. This test stress is less than the modulus of rupture.

The worth of such a standard test, to which all poles are subjected, is open to question. It is felt in some quarters that the test weakens the pole to some extent as timber fibres are actually broken during the test.

B. PERMISSIBLE STRESS

The permissible stress is the value of the stress used in the calculation of the maximum moment of resistance of the pole. The value used for the permissible stress takes the safety factor into account, as illustrated in the previous Section.

Australian practice (ESAA, 1990) uses the following factors in calculating the permissible stress. The load limit used is 40% (equivalent to a safety factor of 2,5) of the ultimate extreme fibre stress (UEFS) for a treated pole subjected to short duration load. The UEFS for *E. saligna* is given as 70MPa, resulting in a permissible stress of $70 \times 0,4 = 28\text{MPa}$.

SABS 0163 (1980) describes a different method (compared to calculation from the modulus of rupture and a safety factor) of obtaining a figure for permissible stress. The term "grade stress" is used to describe a stress value for which the probability of failure is small. It is calculated by dividing the test stress by a factor of 2,22. This factor of 2,22 is equivalent to a safety factor as it allows for load duration, design errors and workmanship. The grade stress for the bending of round poles is thus $55/2,22 = 24,8 \text{ MPa}$ (for a "55MPa" pole).

This grade stress is multiplied by a series of factors in order to obtain the permissible stress for bending:

$$\text{permissible stress} = \text{grade stress} \times k_1 \times k_2 \times k_3 \times k_4 \quad \text{Equation 3.13}$$

where:

k_1 : duration of load

(1,5 for wind load, 1,25 for load durations up to three months, 1 for permanent loads.)

k_2 : load sharing

(1 for a single load-carrying member, 1,15 for connected members subjected to the same load, deflected the same and not more than 600mm apart.)

k_3 : type of structure

(1,1 where the consequences of failure are small, 1 for other structures.)

k_4 : quality of fabrication

(1,05 for components that comply with an SABS specification)

The product of the factors, for a wind-loaded single member, where the consequences of failure are significant, fabricated from components that comply with an SABS specification, becomes:

$$k_1 \times k_2 \times k_3 \times k_4 = 1,5 \times 1 \times 1 \times 1,05 = 1,575$$

The permissible stress for an intermediate line pole under wind load is thus
 $24,8 \times 1,575 = 39,1$ MPa.

C. RUPTURE STRESS

Rupture stress or, more commonly, the modulus of rupture is the stress at which the pole will rupture (that is, at which it will break). ESAA (1990) uses the term ultimate extreme fibre stress for the rupture stress.

The MOS Act (1983) (Electrical Machinery Regulation 14) specifies that "for wooden members not continuously loaded" a factor of safety of 2,7 should be used, "based on the modulus of rupture". Data on the modulus of rupture is not given in either the MOS Act (1983) or in the Code of Practice (SAIEE, 1966)

Publications are available which provide information on the modulus of rupture for poles produced from different species of timber. A publication produced by the South African Forestry Research Institute (BANKS, et al., 1977) lists many species of timber of different (world-wide) origins. *Pinus radiata* (South Africa) and *Pinus radiata* (New Zealand) are listed and the moduli of rupture given as 101MPa and 58MPa respectively. The table below lists the South African data from this and other publications.

Botanical Species	Average Modulus of Rupture (MPa)	Source
Pinus radiata	86	SABS 330 (1951)
Pinus radiata	84	SABS 753 (1964)
Pinus radiata	87	Krogh (1966)
Pinus radiata	101	Banks, <u>et al.</u> (1966)
Eucalyptus saligna	72	SABS 330 (1951)
Eucalyptus saligna	72	SABS 753 (1964)
Eucalyptus saligna	74	Krogh (1966)

The Australian Code of Practice (ESAA, 1990) gives a full list of "typical Australian timbers" each with its ultimate extreme fibre stress (the modulus of rupture).

Timber produced in different countries cannot however be compared unless it is tested according to the same standards and procedures and is grown under the same conditions. The differences between SABS 754 (1982) and ESAA (1990) for the same species (*E. saligna*) is not only a matter of terminology ("modulus of rupture" versus "ultimate extreme fibre stress") but also a matter of climate. The strengths of poles produced from the same species grown in different climates will be different.

It can be concluded from the above discussion and data that the choice of a modulus of rupture for use in South African design calculations is not at all clear. The use of a low value (equal to the test value of 55MPa) may result in an overdesigned, comparatively expensive, line, because of the resulting shorter spans. The use of too high a value may result in the line failing in use.

The Western Cape Region of Eskom has used 84MPa (SABS 753, 1964) for the modulus of rupture for *Pinus radiata* for some years. Spans, in general, have been limited because of the terrain and close cultivation (for example vineyards) so that poles with a smaller diameter could have been used without making any difference to the final design. The current trend towards longer spans means that the limitations imposed on the designs by any factor (in this case the uncertainty concerning the modulus of rupture) will need to be investigated. Additional comment is also made when South African practice is analysed in Chapter 4.

3.5 POLE FOUNDATIONS

It is somewhat of an overstatement to call a hole in the ground a "foundation". Yet that is normally the only support given to intermediate structures on a rural distribution line. The hole is dug by hand or by machine, the excavated soil is replaced around the pole and tamped down and the "foundation" is complete.

Foundation engineering has been defined as the "art and science" of applying engineering judgement and the principles of soil mechanics (Bowles, 1977). Although the science of soil mechanics has progressed rapidly since the thirties, the design of a foundation still depends to a large extent on the application of engineering judgement. Foundation design, particularly for isolated poles, is not an exact science, as foundation loads and soil properties are not likely to be known to better than within 10 to 20% (Bowles, 1977).

The task of the designer is to balance the overturning moment of the applied load against the resisting moment of the soil. The applied load is caused by the wind pressure acting against the exposed area of conductors, pole and structure (see Parts 3.4.1 to 3.4.3 in the previous Section for details of the calculations). The resistance of the foundation to overturning of the pole is a function of the effective area of the buried part of the pole pushing against the soil and also a function of the bearing capacity (also known as the resisting properties) of the soil.

The designer needs to have at his disposal three sets of data: the pole data (diameter and setting depth), the overturning moment being applied to the pole (the force being applied to the pole and its distance of application from ground level), and the bearing capacity of the soil. In addition to this data he will need formulae which will enable him to design the foundation. A safety factor, to allow for errors in data values or in calculation or in construction, is also required.

The data relating to the pole can be changed.

The setting depth of the pole and/or the effective diameter of the pole can be changed.

The data relating to the applied moment can be changed.

The force being applied to the pole can be changed by decreasing or increasing the span. The arm of the moment can be changed by moving the point of action of the force up or down the pole.

The soil conditions for which the foundation is being designed cannot be changed. The design is, however, totally dependant on a correct assessment being made of the properties of the soil, so that the design can be made to suit these properties.

The intention of the writer, in this Section, is only to present the information relating to the formulae used by different designers. It is felt that evaluations and objective comparisons of the formulae are beyond the scope of this thesis. Such evaluations or comparisons would require in depth investigations and experimentation and could indeed contain sufficient material for a Civil Engineering Master's thesis on foundation design for rural lines.

This Section is divided into eight Parts. The first Part discusses soil and soil types and provides typical values for soil bearing capacity. Three examples of below-ground pressure distribution for a single-pole structure are shown. The next six Parts each discuss different theories and the resulting formulae that are used for designing single-pole foundations. The last Part summarises the information presented previously on the different approaches to the foundation design.

3.5.1 THE PROPERTIES OF THE SOIL

The major problem with designing any foundation lies in establishing the load-resisting properties of that particular portion of ground where the foundation is going to be put. Proper tests (involving excavations, laboratory tests and/or on-site tests, etc) to establish the bearing capacity of the soil for a large foundation are essential and also form a comparatively minor part of the total cost of the project. Doing such tests for each pole foundation (one every 100m to 150m or so) for a rural line will add costs without proportionate benefits.

Soil can be classified into four groupings, depending on grain size. These are: gravel, sand, silt and clay. Of the four groups only clay is an inherently cohesive material, the other three being inherently cohesionless. However, silt will exhibit cohesion when wet (Bowles, 1977).

Naturally occurring soils (as listed in Figure 3.03) consist of mixtures of grain sizes and soil types. A "well-graded" soil would include a wide range of grain sizes in contrast to a "poorly-graded" soil where the range of sizes would be narrow.

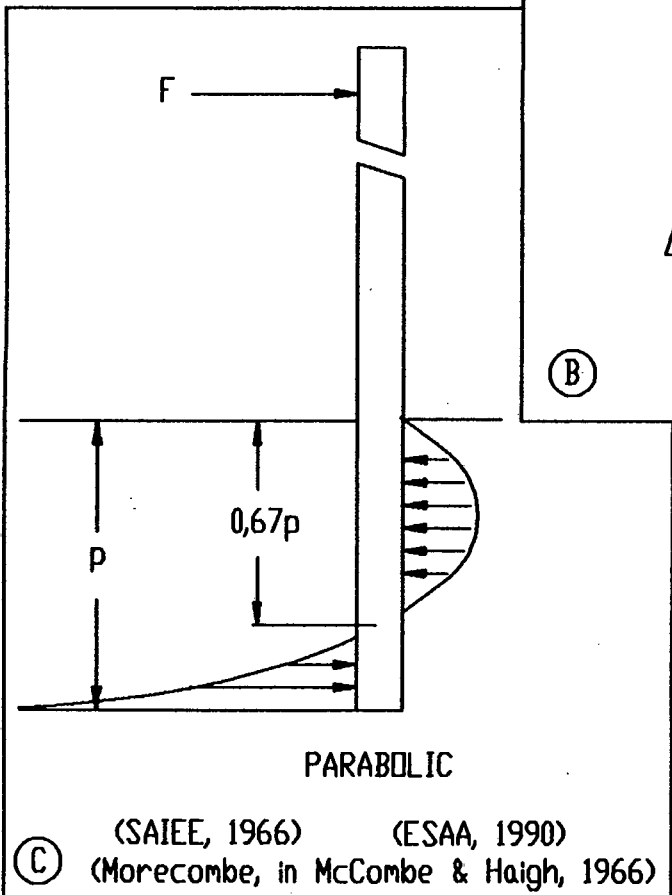
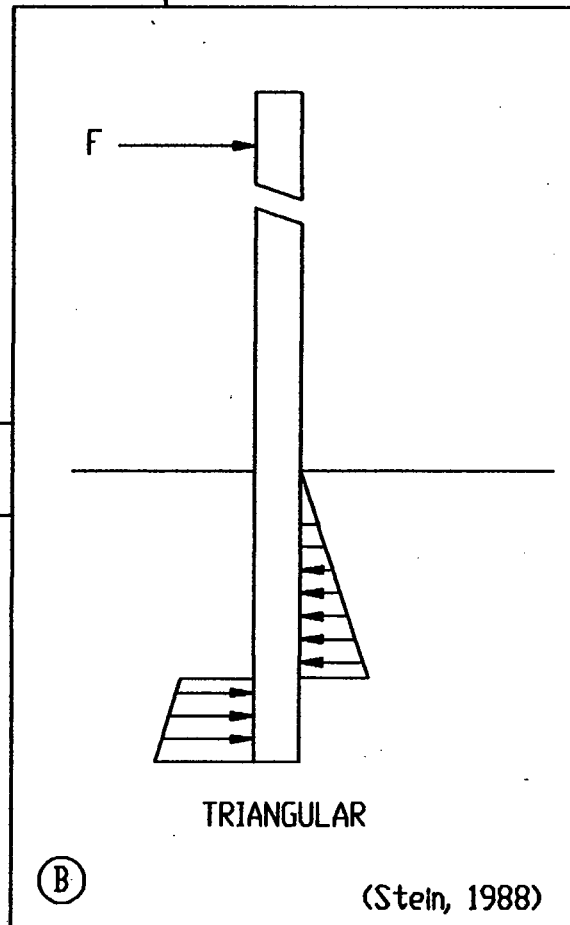
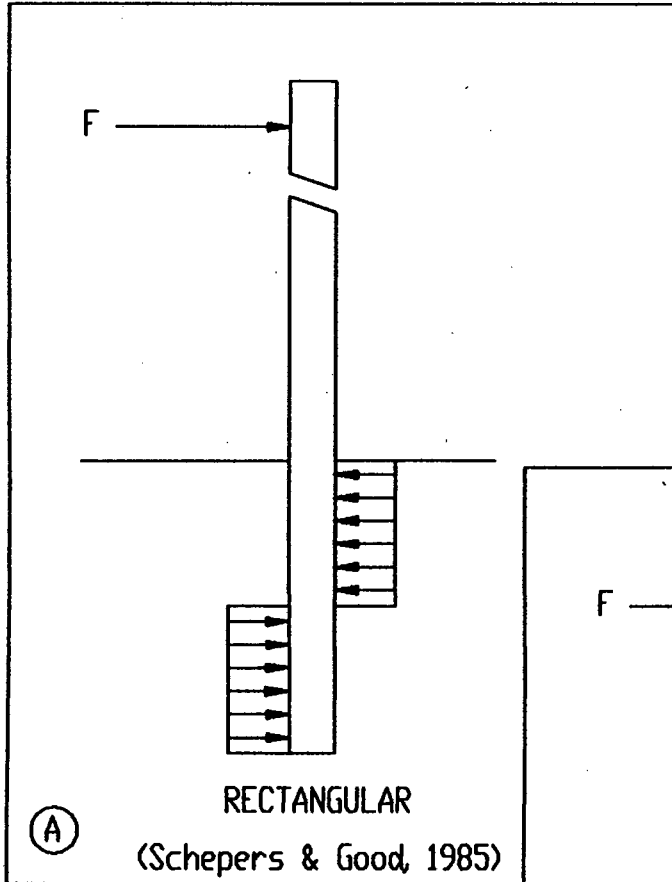
Three of the design formulae (those from SAIEE, 1966; Morecombe (1929) (in McCombe & Haigh, 1966); Schepers & Good, 1985) given later on in this Section cover the whole range of soil types. That of Stein (1988) covers only clay soils. The dates of the derivation of these formulae cover a period of more than twenty years. Some use apparently different properties of the soil and are based on different below-ground pressure distributions, which are shown in Figure 3.04.

One of the major problems that the writer experienced in trying to achieve at least a reasonable understanding of foundation design is that the terminology and the associated values for the variables are different for the different countries of origin. It appears from the literature studied that tables of "safe bearing capacity" for the different soil types have different ranges of values depending on their locality of derivation and use. Data produced in the USA is based on the American customary usage of names of soil types, that produced in Britain is based on British usage, and so on. A "stiff clay" would have a different range of values for safe bearing capacity, depending on the country of origin of the data. It is for this reason that the different authors' terminology and typical values for soil properties are used. The formulae are however rewritten to, as far as possible, use the common symbols and units used throughout the thesis.

	TYPE AND DESCRIPTION OF SOILS	maximum safe bearing capacity kPa
Non-cohesive soils	Compact, well-graded gravels, sands, and gravel-sand mixtures; permanently above all water tables	392 - 490
	Compact, well-graded sands, gravels, and gravel-sand mixtures; possibly below the water-table at any stage of the life of the structure	196 - 245
	Compact but poorly-graded sands, gravels and gravel-sand mixtures; permanently above all water-tables	196 - 392
	Loose sands	by test only
Cohesive soils	Very stiff clays, sandy clays, silty clays, sandy silts, silty sands	392 - 490
	Stiff clays, sandy clays, sandy silts, silty sands	196 - 392
	Firm clays, sandy clays, sandy silts, silty sands	98 - 196
	Soft clays, sandy clays, sandy silts, silty sands	49 - 98
	Very soft clays, sandy clays, silty clays, clayey silts and clayey sands	0 - 49

Extracts from Appendix B, SBR (1970)

FIGURE 3.03



BELOW-GROUND
PRESSURE DISTRIBUTION

FIGURE 3.04

The detailed analysis of designs, in Chapter 4, is confined to eight selected South African designs. It is for the this reason that data from the South African statutory Standard Building Regulations (SBR, 1970) is quoted in Figure 3.03, in order to present the South African nomenclature and data.

The experienced soil technician would know what type of soil he is examining and could thus classify it and determine its range of bearing capacities.

3.5.2 POLE FOUNDATIONS : SOUTH AFRICAN CODE OF PRACTICE

The Code (SAIEE, 1966) gives a formula for a single pole foundation which is based on the parabolic distribution of below-ground pressure. The formula enables the designer to calculate what the "safe bearing pressure" should be in order to support the pole under wind load conditions.

The required safe bearing pressure may be calculated from:

$$q_p = 12F(h + 0,67p)/kd_h p^2 \quad \text{kPa} \quad \text{Equation 3.14}$$

where:

q_p is the safe bearing pressure (kPa)

F is the transverse load on the structure (kN)

h is the height above ground level at which F acts (m)

p is the depth of the foundation (m)

k is a shape factor

(= 1 for a plane face; = 0,85 for a cylindrical face)

d_h is the diameter of the foundation hole (m)

(Note: The factor 0,67 defines the depth of the fulcrum below ground level (see Figure 3.04).)

If the calculations show that permissible values of bearing capacity are exceeded then the effective area of the buried part of the pole should be increased. The safe bearing pressure for an "average soil" is given as 345kPa for "average foundation depths".

The Code suggests that the effective bearing area may be increased by means of "kicking blocks" (baulks of timber) fixed to the pole at the base and at one third of the depth from ground level in order to take the transverse load. It is stated that "the effective bearing area may also be increased by consolidating the area around the pole with soil cement or by the use of boulders well rammed into the hole."

Example:

The required bearing pressure is calculated as below:

The following data from Part 3.4.3 of the previous Section is required:

transverse load on the structure ($F_t = F$) = 2,852kN

height above ground level at which it acts (h) = 7,99m

Additional data required:

shape factor (k) = 0,85

average diameter of the foundation (d_f) = 0,21m

depth of the hole (p) = 1,8m

$$q_p = 12F(h + 0,67p)/kd_f p^2 \quad \text{kPa} \quad \text{(Equation 3.14)}$$

$$= 12 \times 2,852(7,99 + 0,67 \times 1,8)/(0,85 \times 0,21 \times 1,8^2) = 544\text{kPa}$$

which is well in excess of the bearing capacity of 345kPa of "average" soil.

Decreasing the span to 100m reduces this required bearing capacity to 396kPa, which is still more than the figure given above for "average" soil. Note that no safety factor has been used.

3.5.3 MORECOMBE'S FORMULAE FOR SOIL RUPTURING INTENSITY

These formulae according to Morecombe (1929) (also quoted in McCombe & Haigh (1966)) are used to calculate the moment of resistance of the soil for a pole planted to a certain depth and subjected to an overturning moment.

The first formula is based on the fact that a support tends to pivot about a fulcrum two thirds of its buried depth (for a parabolic form of stress distribution, as shown in Figure 3.04C). The formula according to Morecombe (1929) is:

$$M_r = q_i d_p p^3 / 12 \quad \text{kNm} \quad \text{Equation 3.15}$$

where:

M_r is the moment of resistance (kNm)

q_i is the "rupturing intensity" of the soil (kPa/m)

d_p is the average diameter of buried part of pole (m)

p is the planting depth (m)

Note: q_i can be defined as a bearing capacity of the soil that increases with increasing depth.

The moment of resistance (M_r) is compared to the total overturning moment (M_o), the product of the transverse force and the distance of the point of action of the load from the fulcrum.

M_o is given by:

$$M_o = F(h + 0,67p) \quad \text{kNm} \quad \text{Equation 3.16}$$

where:

F is the transverse load (kN)

h is the height above ground at which it acts (m)

By equating these two moments and rearranging, the following formula is obtained:

$$q_i = 12F(h + 0,67p) / d_p p^3 \quad \text{kPa/m} \quad \text{Equation 3.17}$$

This is similar to the SAIEE (1966) formula (Equation 3.14) except for the use of p^3 instead of p^2 in the divisor and the fact that a shape factor is not used by Morecombe.

The second formula according to Morecombe uses a simplification of this stress distribution which is to assume that it is a straight-line distribution (also called a triangular distribution) as shown in Figure 3.04B. The fulcrum is then at 0,71 of the buried depth.

In this case the complete formula becomes:

$$q_i = 10F(h + 0,71p)/d_p p^3 \quad \text{kPa/m} \quad \text{Equation 3.18}$$

The following typical values for q_i are given in McCombe and Haigh (1966) for use with Morecombe's formulae:

Soil Type	q_i (kPa/m)
loamy or wet soil	190
loose sandy soils	270
average (clay) soils	410
firm gravel	820

Example:

The required rupturing intensity is calculated as below:

The following data from Part 3.4.3 of the previous Section is required:

transverse load on the structure ($F_t = F$) = 2,852kN

height above ground level at which it acts (h) = 7,99m

Additional data required:

average diameter of the foundation (d_h) = 0,21m

depth of the hole (p) = 1,8m

$$q_i = 12F(h + 0,67p)/d_p p^3 \quad \text{kPa/m} \quad \text{(Equation 3.17)}$$

$$= 12 \times 2,852(7,99 + 0,67 \times 1,8)/(0,21 \times 1,8^3) = 257\text{kPa/m}$$

which is less than the figure quoted above for average soils.

3.5.4 POLE FOUNDATIONS : AUSTRALIAN GUIDELINES

The (draft) guidelines issued by the Electricity Supply Association of Australia (ESAA, 1990) state:

"Notwithstanding the requirements [for load bearing], a free-standing wood pole less than 24 metres in length which is set directly into the ground should be set in the ground to a depth of not less than 0,6 metres plus one tenth of the pole length."

This reduces to: $p = 0,6 + 0,1L$ m

where:

p is the pole embedment depth (m)

L is the overall length of the pole (m)

For an 11m pole the embedment depth is thus 1,7m.

The above relation has been around for some time, although no other reference to it has been found in the documents consulted. It is relevant only in that it specifies a minimum embedment depth for a distribution line pole.

The mechanics of pole foundations are described in Appendix C of the Australian guidelines (ESAA, 1990). The relations used, with symbols changed for consistency, are given below. The below-ground pressure distribution used is that of a parabola (Figure 3.04C).

In the following equations the symbols have the following meanings:

q_k is the "passive soil reaction per unit depth" (kPa/m)

F is the transverse load at the pole tip (kN)

h is the height above ground level at which F acts (m)

p is the depth of the foundation (m)

d_h is the diameter of the foundation hole (m)

p_j is the depth of the fulcrum below ground level (m)

(In the formulae below, the load (F) is defined to act at the pole tip and the height at which it acts (h) is therefore the height of the pole above ground level. The applied moment is, of course, not defined differently, only its expansion into force and arm-of-force.)

The position of the fulcrum, or pivot depth, is given by:

$$p_j = 0,67p(1 + 0,75p/h)/(1 + 0,67p/h) \quad \text{m}$$

this can be simplified in purely mathematical terms to:

$$p_j = 0,67p + 0,67p(0,083p/(h+0,67p)) \quad \text{m}$$

For a typical 11m pole, p would be 1,8m and h therefore 9,2m. This second term thus becomes:

$$0,67p(0,0144) = 0,0096p$$

The omission of the second term would cause less than 1,5% error in the calculation of the pivot depth. This could then be simplified to 0,67p (which is the same as that used by SAIEE (1966) and Morecombe (1929)).

The relation given by ESAA (1990) for the limiting or maximum soil reaction per unit depth is:

$$q_k = 12F(h + 0,75p)/d_h p^3 \quad \text{kPa/m} \quad \text{Equation 3.19}$$

(This formula is almost identical to that of Morecombe (1929) which was detailed in Part 3.5.3.)

Typical values quoted (ESAA, 1990) for q_k are:

Quality	Soil Type	q_k (kPa/m)
"Good"	hard clay, well bonded sand & gravel	600
"Average"	medium clay, well bonded sandy loam, bonded sand & gravel	300
"Poor"	soft clay, poorly compacted sand	150

Example:

The required soil reaction is calculated as below:

The following data from Part 3.4.3 of the previous Section is required: total imposed moment is 22,774kNm

Additional data required:

average diameter of the foundation (d_f) = 0,21m

depth of the hole (p) = 1,8m

An 11m pole is used and thus the tip height above ground level (h) is $11 - 1,8 = 9,2$ m

The imposed force (F) is given by $22,774/9,2 = 2,475$ kN

The required soil reaction is given by:

$$q_k = 12F(h + 0,75p)/(d_f p^3) \text{ kPa/m} \quad (\text{Equation 3.19})$$

$$= 12 \times 2,475(9,2 + 0,75 \times 1,8)/(0,21 \times 1,8^3) = 255\text{kPa/m}$$

which is close to that for "average" soil (300kPa/m)

3.5.5 CURRENT PRACTICE IN THE UNITED STATES OF AMERICA

Current practice in the U.S.A. (Fink and Beaty, 11th edn.) is to ignore foundation design for woodpole structures as "the strength of the pole foundation is difficult to reduce to figures ...". "Failure of the foundation, that is, a considerable movement of the pole in the ground, is of little consequence except for the inconvenience and expense of straightening up the line and retamping the poles." Foundation (pole setting) depths have been established by experience.

The industry-wide U.S.A. specification ANSI 05.1 (Specifications and Dimensions for Wood Poles) includes the standard setting depth (foundation depth) of 6 feet (1,83m) as part of the specification for the specific pole classes. A pole is classed according to the load it can withstand at 2 feet (0,610m) from the top without the designated modulus of rupture being exceeded at the ground line. Each class is thus based on a length / diameter relationship for each particular timber species. As an example of the proposed metricated ANSI 05.1, a Class M9 pole classification will be an 11m pole with a setting depth of 1,8m. The pole would hold a load of 6,9kN applied 600mm from the top. (REA, 1982)

3.5.6 THE EFFECT OF BACKFILL QUALITY ON FOUNDATIONS

U.S.A. practice, as has been mentioned above, is not to design foundations but to set the pole to a predetermined depth of 1,83m.

Schepers & Good (1985), in a paper presented at the IEEE Rural Electric Power Conference, present the other side of the coin, that the specified setting depth of the pole may be insufficient for certain applications. Their proposals are specifically aimed at eliminating short stays (stays for which the anchor points are comparatively close to the pole) by increasing either the effective foundation width or the pole setting depth or by improving the backfill.

The analysis is based on their assumption that when the backfill is more dense than the surrounding soil then the equivalent pole diameter is increased and vice versa.

The formula they derived for pole setting depth is based on the soil pressure distribution shown in Figure 3.04A. The formula given below has been derived from their proposals. It has been metricated and the symbols changed.

$$p = 2F/d_o q_r + (4Fh/d_o q_r + 2F^2/d_o^2 q_r^2)^{0.5} \quad \text{m} \quad \text{Equation 3.20}$$

where:

p is the pole setting depth (m)

F is the transverse force applied to the pole (kN)

d_o is the equivalent pole diameter (m)

q_r is the "resisting soil pressure" (kPa)

h is the height above ground level at which F acts (m)

Typical values given for q_r range from about 190kPa to 700kPa with 380kPa being that for an average good bearing soil.

For soil backfill the equivalent pole diameter is given by the formula: $d_o = d_p \sin a_s$ m

where d_p is the pole diameter and a_s is given as a function of the angle of friction between pole and the backfill.

A value of 60° (which is quoted in the paper as being "reasonable for normal soil conditions") for α_s makes $\sin \alpha_s = 0,866$. (Compare this with the "shape factor" of 0,85 used in the SAIEE (1966) formula.)

Example: Calculation of resisting soil pressure:

Using Equation 3.20 and the data calculated previously :

transverse load on the structure ($F_t = F$) = 2,852kN

height above ground level at which it acts (h) = 7,99m

average diameter: buried part of the pole (d_p) = 0,21m

equivalent pole diameter (d_e) = 0,866 d_p = 0,18m

foundation hole diameter (d_h) = 0,5m

$$1,8 = \frac{2 \times 2,852}{0,18q_r} + \sqrt{\frac{4 \times 2,852 \times 7,99}{0,18q_r} + \frac{2 \times 2,852^2}{0,18q_r^2}}$$

(Equation 3.20)

A value of 191kPa is obtained for the resisting soil pressure (q_r) by successive approximation. This value is well below the given value of 380kPa for an average soil.

[Note:

Equation 3.20 is given as: $p = 2F/d_e q_r + ((4Fh/d_e q_r) + (2F^2/d_e^2 q_r^2))^{0,5}$ m

which is an equation of the form: $a = b + (c + d)^{0,5}$

By rearranging this to $a - b = (c + d)^{0,5}$ and squaring both sides, and rearranging again, the following new form is obtained for Equation 3.20:

$$p^2 = (4F/d_e q_r)/(p + h - F/2d_e q_r) \quad m^2$$

The term $F/2d_o q_r$ has a calculated value of 0,04m (using the information given above) whereas $p = 1,8m$ and $h = 7,99m$. Omission of the term $F/2d_o q_r$ would cause less than 1% error in the calculation, certainly for values of the order of those used in the example.

The equation can again be rearranged to give:

$$q_r = 4F(h + p)/(d_o p^2) \quad \text{kPa} \quad \text{Equation 3.20A}$$

which is of the same form as Equation 3.14 (SAIEE,1966). The calculated value for q_r is 191,3kPa (compared to 190,6kPa for the complete formula.)

The authors state that their proposals are aimed at determining how best to improve the load-resisting capability of a distribution line pole by improving the backfill or by increasing the setting depth. Their proposals are aimed specifically at increasing the pole setting depth beyond the standard 6 feet (1,83m) used for rural lines in the U.S.A. They state that "the method is not valid for justifying decreased setting depths but is believed to be on the conservative side for predicting the benefits of increased setting depth".

Figure 3.05 illustrates the concepts used in the proposals of Schepers and Good (1985) for the calculation (as given below) of the effect of an improved backfill on the effective diameter of the hole.

$$d_o = d_h \sin(a_b + \sin^{-1}((d_p/d_h) \times \sin(180 - a_s + a_b))) \quad \text{m} \quad \text{Equation 3.21}$$

where:

d_o is the equivalent pole diameter (m)

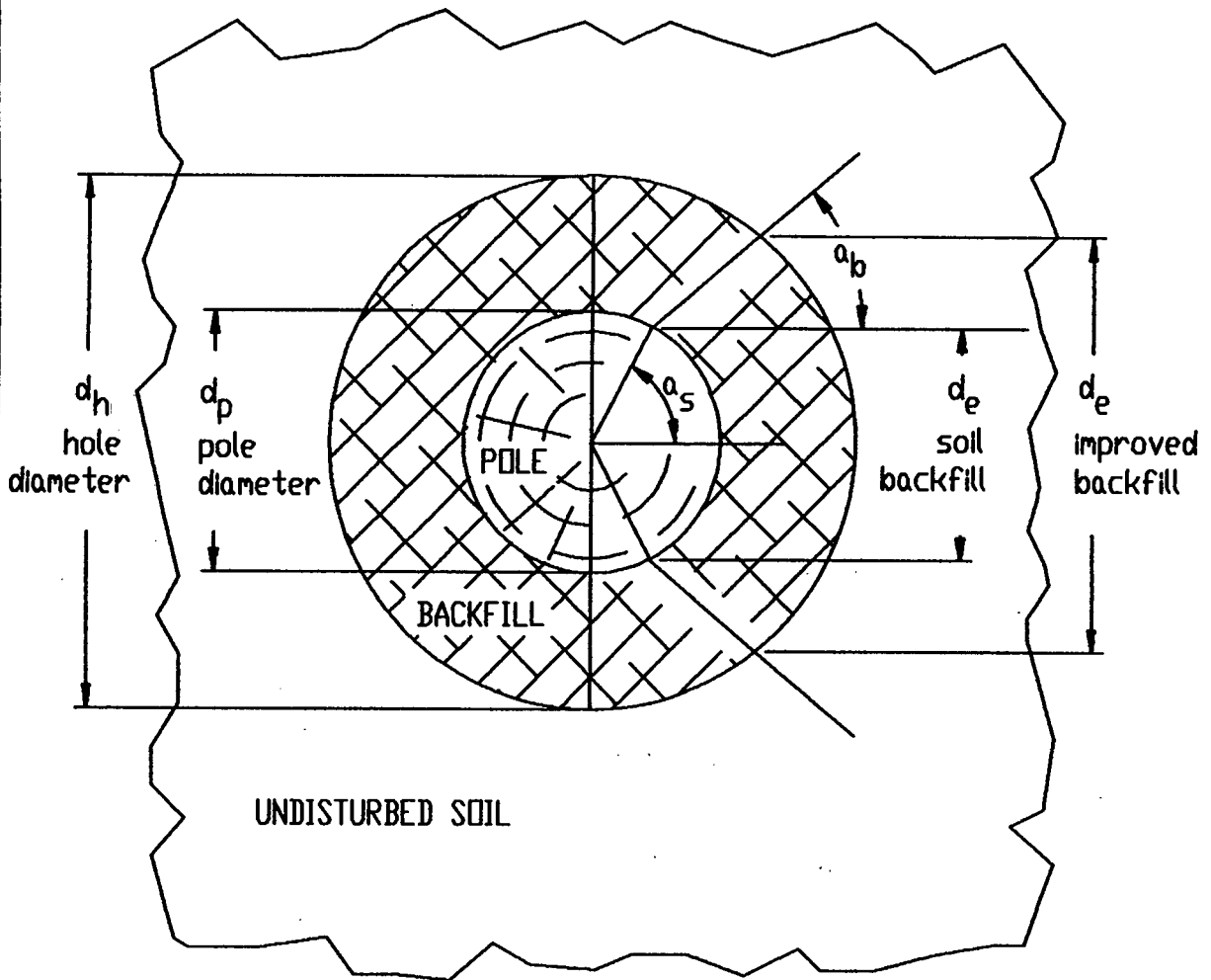
d_h is the hole diameter (m)

d_p is the pole diameter (m)

a_s is given as a function of the angle of friction between the pole and the backfill.

a_b is given as the internal angle of friction of improved backfill material.

It is stated in the paper that "with reasonable backfill tamping a value of 30° [for a_b] should be easily achievable".



The better the backfill is compacted and/or the more dense the backfill is compared to the surrounding undisturbed soil, the larger will angle α_b become and hence also the effective diameter of the foundation.

SECTION THROUGH EMBEDDED POLE TO ILLUSTRATE THE EFFECT THAT IMPROVED BACKFILL WILL HAVE ON EFFECTIVE FOUNDATION DIAMETER.

FIGURE 3.05

Example: Effect of improved backfill

A new value is obtained for d_e (for an improved backfill) by using Equation 3.21 and data given previously in this Part: ($a_s = 60^\circ$; $a_b = 30^\circ$; $d_p = 0,21\text{m}$; $d_h = 0,5\text{m}$)

A calculated value of 0,34m is obtained for d_e , which is better than the previous value for d_e (0,21m), for a soil backfill, used in the previous example.

Schepers and Good (1985) have recommended that soil tests be carried out in the area of the particular utility before this design procedure is used. "The test-loading of an example pole in representative soils and under representative soil moisture conditions is an aid to the evaluation" [of the soils].

The main value of the paper presented by Schepers & Good (1985) is that they attempt to present a "better" value for the "effective diameter" of the foundation as used in the calculations.

3.5.7 STEIN'S UNIFIED FORMULA FOR POLE FOUNDATIONS

Stein (1988), in a paper presented at an IEE conference on overhead line design and construction, has proposed a "unified theory for the design of pole foundations". It is based on the deformation characteristics of the soil subgrade (otherwise known as "the lateral coefficient of subgrade reaction"). A triangular form of stress distribution has been used (see Figure 3.04B). Stein's intention with his paper was to present a theory which included both cohesive and non-cohesive soils in a single formula. However, the data on soils in his paper refers to only clay or cohesive soils.

The design formula below, with change of symbols, has been derived from his proposals.

$$q_u = (6Fh/26,2d_h p^3)^{0,5362} \text{ kPa} \qquad \text{Equation 3.22}$$

where:

- q_u is the "ultimate cohesion" of the soil (kPa)
- F is the applied force (N)
- h is the height above ground of the force (m)
- d_h is the diameter of the foundation hole (m)
- p is the pole setting depth (m)

The "ultimate cohesion" of the soil can be defined as the bearing capacity the soil would have under load just before the cohesion failed.

The following ranges of values for q_u are given in the paper:

Soil Type	q_u (kPa)
very soft clay	0 - 25
soft clay	25 - 50
medium clay (soft)	50 - 75
medium clay (wet)	75 - 100
stiff clay (wet)	100 - 150

"Normal soil" is quoted as having a value of 100kPa for q_u .

Example: Calculation of the ultimate cohesion required:

Using Equation 3.22 and the data calculated previously :

transverse load on the structure ($F_t = F$) = 2 852N

height above ground level at which it acts (h) = 7,99m

average diameter of the pole (d_h) = 0,21m

setting depth of pole (p) = 1,8m

$$q_u = ((6Fh)/(26,2d_h p^3))^{0,5362} \text{ kPa} \quad (\text{Equation 3.22})$$

$$= (6 \times 2\,852 \times 7,99 / 26,2 \times 0,21 \times 1,83)^{0,5362} = 88\text{kPa}$$

which is close to the value given for "normal soil".

3.5.8 COMPARISONS OF THE FORMULAE FOR POLE FOUNDATIONS

The five formulae presented in the previous Parts are given below. The values calculated for the bearing property of the soil (q), using the same values for the variables, are given with each formula.

SAIEE (1966):

$$q_p = 12F(h + 0,67p)/kd_h p^2 \quad \text{kPa} \quad (\text{Equation 3.14})$$

(= 544kPa)

Schepers & Good (1985):

$$q_r = 4F(h + p)/d_s p^2 \quad \text{kPa} \quad (\text{Equation 3.20A})$$

(= 191kPa)

Morecombe (1929):

$$q_i = 12F(h + 0,67p)/d_p p^3 \quad \text{kPa/m} \quad (\text{Equation 3.17})$$

(= 257kPa/m)

ESAA (1990):

$$q_k = 12F(h + 0,75p)/d_h p^3 \quad \text{kPa/m} \quad (\text{Equation 3.19})$$

(= 255kPa/m)

Stein (1988):

$$q_u = (6Fh/26,2d_h p^3)^{0,5362} \quad \text{kPa} \quad (\text{Equation 3.22})$$

(= 88kPa)

These calculations were all done for a span of 150m of Mink conductor and a total pole length of 11m, set to a depth of 1,8m and exposed to a transverse wind pressure of 700Pa.

The variables, such as those for force (F), height of force application above ground level (h), and foundation or setting depth (p), are all used in the same sense in all the formulae. None of the formulae uses a factor of safety directly.

The foundation formulae given above use different variables for the load-resisting property of the soil. Apparently the first two use the same property of the soil, the difference in the multiplication constant (12 compared to 4) accounting for virtually all the difference between the two results. The second two formulae use a different load-bearing property of the soil which is proportional to the depth of the foundation. The third formula uses yet another property of the soil which is related to the cohesion of the soil rather than to its load-bearing properties.

The formulae proposed by Morecombe (1929), ESAA (1990) and Stein (1988) use the cube of the depth and Schepers & Good (1985) and SAIEE (1966) use the square of the depth of the foundation hole. This difference is related to the load-bearing property of the soil being used. Stein, in his paper, states that the "depth cubed" formula was derived from the use of "depth squared" formulae. The dates of the formulae given above contradict this as the formula of Morecombe (1929) ("depth cubed") predates all the others.

The biggest difference between the various formulae is in their use of a variable for the diameter or width of the foundation. Morecombe (1929) (in McCombe & Haigh, 1966) uses the pole diameter and SAIEE (1966), ESAA (1990) and Stein (1988) each use the foundation (hole) diameter. The SAIEE (1966) definition and use of the variable is, however, ambiguous and it appears from the text that its actual size would depend on the type of backfill used. Schepers & Good (1985) use an expression for an equivalent diameter which depends on the quality of the backfill.

Only the treatment of Schepers & Good (1985) takes an analytical look at the construction of the foundation itself in defining an equivalent pole diameter (See Figure 3.05). This aspect is probably the most critical and would need further consideration.

Neither Morecombe (1929) (in McCombe & Haigh, 1966), ESAA (1990) nor Stein (1988) use shape factors for calculation of an effective diameter of the foundation. SAIEE (1966) uses a factor of 0,85 for a (cylindrical) pole and Schepers & Good (1985) use factors which are functions of "angles of friction" of the soil and backfill.

The use of the variable for the equivalent diameter in the treatment of Schepers & Good (1985) means it can be more flexible in its application. However, it should be borne in mind that it is possible to use any of the formulae as a basis and to adapt it to the results of practical tests.

SAIEE (1966), McCombe & Haigh (1966) and Stein (1988) indicate that a safety factor of about 2 should be used. It is not used as part of the formula, however.

The large difference between the SAIEE (1966) and Schepers & Good (1985) formulae is more fully discussed in the introductory pages of Section 4.3.

A proper evaluation and comparison of the formulae would require an investigation of soil mechanics as applied in the different countries in order to establish or confirm a common nomenclature and definition of soil properties. The soil in a suitable site would then be tested in order to obtain the required load-bearing properties. The formulae could then be tested in practice by designing pole foundations, embedding poles and testing the design by applying the design load and also testing to failure.

The simplest conclusion (which evades the issue of foundation design completely) is to adopt the USA practice of predetermined pole setting depths for each strength class of pole. However, as has been pointed out by Schepers & Good (1985), it is suspect to use only one foundation depth for all strength classes of pole.

3.6 THE SPACING OF THE CONDUCTORS AT THE CROSSARM STRUCTURE

The purpose of this Section is to present, evaluate and compare formulae which have been developed for the calculation of conductor spacing. The spacing between conductors at the crossarm should be large enough to avoid arcing between the conductors at midspan.

Wind conditions causing gusts or updraughts can cause two conductors to swing towards each other. The likelihood of two conductors approaching too close to each other because of the effect of wind is highest if they are attached at the same level. The longer the span, the more chance there is of the two conductors approaching within arcing distance of each other at midspan. The spacing of the conductors attached at the same horizontal level therefore determines the maximum span for which the particular configuration can be used.

When conductors are attached above one another, then a sudden release of mass (such as an accretion of snow or ice) on the lower conductor could cause the lower conductor to whip vertically up and approach too close to the conductor above it. The vertical spacing of the conductors should therefore be large enough to prevent them from coming within arcing distance of each other due to this cause. This is not considered to be a problem in South Africa.

The geometric positioning of the conductors on the pole-top structure is prescribed by two factors:

1. the minimum electrical clearance (as specified for South African practice in the MOS Act (1983), SAIEE (1966), and Eskom (1974)).
2. an additional clearance to account for conductor contra-movement to prevent arcing between two phase conductors.

This Section is divided into seven Parts. The first five Parts each present and evaluate a different formula for the calculation of conductor spacing. Part 3.6.6 analyses and compares these five formulae. The subject of conductor galloping, since it may also affect how far conductors should be spaced, is discussed in the last Part.

3.6.1 AN EARLY THEORY ON CONDUCTOR SPACING

Thomas (1928) has discussed the problem of conductor contact in the span in the following way. When a strong steady wind blows across the run of the span it can be expected that the relative positions of the conductors are not affected as the same wind force affects all the conductors. The wind essentially blows parallel to the ground. The higher the wind speed the less turbulence is produced high off the ground.

When the wind blows horizontally across the conductors its action on them is to increase the tension in the conductors. This increase in tension further resists any change to the shape of the catenary in the plane of the curve.

However, should the position of the line be such that a component of the wind pressure acts vertically, then the resulting vertical forces could balance or even exceed the downward force of the conductor weight. A line positioned parallel to a ridge or across a rapidly narrowing valley would be subjected to upward wind pressures of this kind. The conductors, with no tension to keep them in position, would be able to move sufficiently to cause a phase-to-phase arc or even contact. In this case it can be clearly seen that wind blowing across particular topographical conditions could be the underlying cause of conductors approaching too close to one another.

Thomas (1928) proposed a formula, based on experience, for safe (midspan) spacing in gusty, windy territory. This formula, after metricating and changing the symbols to be consistent with the other formulae, is given below:

$$c = k_o s_p d_c / w + c_a \quad \text{m} \qquad \text{Equation 3.23}$$

where:

c is the between-conductor spacing (m)

k_o is an "experience factor" which depends on the conductor
(615 for ACSR or 700 for copper)

s_p is the percentage sag of the span (= 100 x sag/span)

d_c is the overall conductor diameter (m)

w is the resultant load under wind conditions

$$w = (w_c^2 + w_w^2)^{0.5} \qquad \text{(Equation 3.4)}$$

c_a is the arcing distance at the line voltage

(0,03 for 11kV and 0,06m for 22kV based on 0,0028m/kV) (Thomas, 1928)

This formula is intended to be used to calculate the required conductor spacing for gusty, windy conditions under which the line is to operate. A lower value of 175 is proposed by Thomas (1928) for k_o in regions not subjected to strong, gusty wind.

(The large values for k_o given above are due to metrication of the original formula for which k_o for calmer conditions for all conductors was given as 1, for ACSR as 3,5 and for copper conductor as 4 in windy conditions.)

3.6.2 CONDUCTOR SPACING: SOUTH AFRICAN CODE OF PRACTICE

The Code of Practice (SAIEE, 1966) quotes a simple formula which gives a "reasonable" horizontal spacing between phase conductors. This formula, metricated and with the symbols changed, is given below.

$$c = l/200 + c_p \quad \text{m} \qquad \text{Equation 3.24}$$

where:

c is the between-conductor spacing (m)

l is the span length (m)

c_p is the phase-to-phase clearance (m)

(0,229m for 11kV; 0,356m for 22kV)

According to SAIEE (1966) the spacing for a vertical configuration could be as low as the phase-to-phase clearance c_p . For a triangular configuration the spacing would normally be less than c .

3.6.3 CONDUCTOR SPACING:
RURAL ELECTRIFICATION ADMINISTRATION, U.S.A.

The standards produced in the U.S.A. for rural electrification between 8,7kV and 24,9kV (REA, 1982) are based on the following relations for horizontal spacing (with symbols changed for consistency):

Minimum horizontal clearance at the supports should not be less than:

$$c = 0,305 + 0,01(V - 8,7) \quad \text{m} \qquad \text{Equation 3.25}$$

for voltages above 8,7V

or less than the clearance based on sag:

$$c = 0,0076V + 0,368(s)^{0,5} \quad \text{m} \qquad \text{Equation 3.26}$$

where:

c is the between-conductor spacing (m)

s is the conductor sag (m) at 15°C with no wind.

V is the system voltage (kV)

Vertical spacing at these voltages is given as 1,02m in REA (1982).

The Standard Handbook for Electrical Engineers (11th edition) (which discusses U.S.A practice), in contrast to SAIEE (1966), proposes that vertical construction should have the same spacing as horizontal construction, with additional clearance for ice-loading, for the reasons given in the introduction to this Section. This factor does not generally need to be considered in South Africa.

3.6.4 McCOMBE AND HAIGH'S FORMULA FOR CONDUCTOR SPACING

McCombe & Haigh (1966) proposed the following formula for horizontal spacing (with symbols and units changed for consistency):

$$c = 2s \sin a \quad \text{m} \qquad \text{Equation 3.27}$$

where:

c is the between-conductor spacing (m)

s is the conductor sag (m)

a is the angle of swing of the conductor (degrees)

when it is subjected to a transverse wind load at 48km/h.

$$\tan a = w_w / w_c \qquad \text{Equation 3.28}$$

where:

w_w is the conductor unit wind load ($= P_w d^a k$)

$$P_w \text{ (wind pressure)} = 0,0463 \times v_w^2 \text{ Pa}$$

(at sea level: derived from SABS (1980))

v_w is the wind speed (km/h)

d_c is the overall conductor + ice diameter (m)

k is the shape factor for a cylinder (0,6)

w_c is the unit conductor weight (N/m)

McCombe & Haigh (1966) use a wind speed of 48km/h (30mph) and P_w thus becomes: $0,0463 \times 48^2 = 107\text{Pa}$. The conditions they assume are for an ice-loaded conductor and that ice-loading and maximum wind do not occur at the same time. The maximum wind speed could be of the order of 123km/h (equivalent to a wind pressure of 700Pa). It is generally accepted that ice-loading of a conductor would not occur under conditions of such high wind speed. Under South African conditions the wind pressure of 700Pa (the minimum statutory requirement (MOS Act (1983))) could be used as it is not generally necessary to take ice-loading into account.

3.6.5 VDE (GERMANY): HORIZONTAL SPACING

The VDE (quoted in McCombe & Haigh (1966)) gives a formula for horizontal spacing (with symbols and units changed for consistency):

$$c = 0,75(s)^{0.5} + V^2/20\ 000 \quad \text{m} \qquad \text{Equation 3.29}$$

where:

c is the between-conductor spacing (m)

s is the conductor sag (m)

V is the system voltage (kV)

The second term is significant only at higher voltages. It is 6mm at 11kV, 24mm at 22kV, 218mm at 66kV, 871mm at 132kV and 8 000mm at 400kV.

3.6.6 COMPARISON OF FORMULAE FOR CONDUCTOR SPACING

The table on the next page presents a comparison between the five formulae for conductor spacing given above. The values chosen for the variables are:

Mink (ACSR) conductor:

weight (w_c): 2,52N/m diameter (d_c): 0,01098m
span (l): 100m sag (s): 1m

wind pressure (P_w): 700Pa shape factor (k): 0,6

wind load (w_w) = $P_w d_c k = 700 \times 0,01098 \times 0,6 = 4,62\text{N/m}$

resultant load (w) = $(w_c^2 + w_w^2)^{0,5}$ (Equation 3.4)
= $(2,522 + 4,612)^{0,5} = 5,26\text{N/m}$

line voltages (V): 11kV and 22kV

sin a (where "a" is the wind angle) is derived from:

$\sin a = w_w / w = 4,62/5,26 = 0,88$ (derived from Equations 3.4 and 3.28)

$k_e = 615$ (ACSR conductor)

$c_a = 0,03\text{m}$ for 11kV and 0,06m for 22kV

$c_p = 0,229\text{m}$ for 11kV and 0,356m for 22kV

$s_p = 100 \times \text{sag/span} = 100 (1/100) = 1\%$

Equation No.	Origin	Equation (spacing =)	Spacing (m)	
			@11kV	@22kV
3.23	Thomas	$k_e s_p d_c / w + c_a$	1,31	1,34
3.24	SAIEE	$l/200 + c_p$	0,73	0,86
3.26	REA	$0,386(s)^{0,5} + 0,0076V$	0,47	0,56
3.27	McCombe	$2s \sin a$	1,76	1,76
3.29	VDE	$0,75(s)^{0,5} + (V)^2/20\ 000$	0,76	0,77

It can be presumed that the development of many (if not all) of these formulae has been essentially empirical. All the formulae have a term which is a function of sag and/or span. All, except for Equation 3.27, have a second term that is a function of the system voltage. The effect of this second term on the horizontal spacing ranges from 6mm (VDE) to 230mm

(SAIEE) for an 11kV system voltage. Yet these two formulae give results which are closest in value for the voltages being considered. The SAIEE formula is the easiest to use.

A particular formula would probably be used by a distribution authority in the initial development of an overall line design philosophy. Once the size range and geometric style of the design has been finalised then it is unlikely that the conductor spacing will be changed. The spacing actually used may be well in excess of that calculated from the formula. For example, REA (1988) use a spacing of over 1m whereas the formula gives a spacing of 0,55m at 22kV. However, the formula should be used as a check during the design of a specific line in order to ensure that the required horizontal clearance is maintained, particularly if the span or sag is particularly large.

The spacing formula can give a guide as to how far the parameters of the line (particularly spans) can be stretched and adequate practical clearances between conductors at midspan still maintained. Other requirements such as clearances for climbing access for live line work, may also influence the conductor spacing.

Practical experience and adjustment of the parameters or factors used, so that local topographical or weather conditions are taken into account, should be used to adapt a formula to local or regional use. Wind speeds, direction and flow patterns (gusts) and ice formation should be taken into account.

3.6.7 GALLOPING OF CONDUCTORS

Wind-generated galloping can be generally defined as a mainly vertical, low frequency, high amplitude vibration caused when wind acts on an ice-coated conductor. (Ratkowski (1968), Nigol and Buchan (1981))

Wind passing around the conductor with an asymmetrical accretion of ice or snow causes torsion and/or aerodynamic lift and thus oscillation or galloping of the conductor (Nigol & Buchan, 1981). The wind has to blow at virtual right-angles to the run of the conductor in order to produce this phenomenon. However, galloping is also said to occur on long spans of stranded conductor under the action of oblique winds (Winants & Reiz, 1970).

It would appear from the above that, under South African conditions, where ice accretion seldom occurs, that galloping will not be a significant problem. Where there is a possibility of galloping occurring, spacing may have to be increased, or spans shortened, to prevent conductor clashing or arcing.

3.7 PRECAUTIONS TO MINIMISE THE EFFECT OF LIGHTNING ON RURAL DISTRIBUTION LINES

The purpose of this Section is to introduce the reader to the precautions that can be taken to minimise the effect that lightning may have on a rural distribution line. The main aim is thus to examine the options the designer has at his disposal and the effect each of these options has on the lightning-related performance and design of the line.

The insulation level of a line is determined by the impulse voltage that can be withstood by the path between a phase conductor and earth. This path runs from the phase conductor, along the insulator, along the crossarm (if any) and down the pole to the ground.

Gaunt, Britten & Geldenhuys (1989) and Eskom (1989) have consolidated current (South African) theories on the effects of lightning on distribution lines and how these effects can be minimised. A summary of the salient points is given in this Section.

Map 3.1 shows the areas of different lightning ground flash intensity for South Africa.

The first two Parts of this Section state what the effects of direct and indirect lightning strikes to a line can be. The third Part discusses the consequences of flashover resulting from a lightning strike and also how line equipment can minimise damage and outages. The fourth Part explains what the impulse withstand level or insulation level of a pole structure means. The last Part discusses the hardware required for the pole structure in order to establish the insulation level and/or to minimise the effect of a lightning strike on the structure or electrical network.

3.7.1 RESULTS OF DIRECT LIGHTNING STRIKES

A direct strike to an unshielded line almost always causes flashover to earth of one or more conductors at the pole nearest the strike.

At low impulse insulation levels (less than about 100kV) flashover will occur at several adjacent poles, typically 3 to 5, depending on the earthing resistance of the poles.

At high impulse insulation levels (1 to 2 MV), flashover may occur at only one structure or not at all. In the latter case a severe impulse voltage may be transmitted to terminal equipment over long distances.

A direct strike to the shield wire of a shielded distribution line, depending on the values of a number of parameters, will either be conducted to earth to some extent or cause a back flashover to the phase conductors. Typical values of 500kV for insulation levels between the shield wire and the phase conductor, and of about 20 ohms for footing resistances, are needed to prevent back flashovers. The ratio of impulse insulation level (in kV) to pole footing resistance (in ohms) should be greater than 20 for significant shielding. The cost of achieving a suitably low footing resistance has an adverse effect on the economic viability of shielded distribution lines.

Surge currents in the phase conductors caused by a back flashover will be lower for a shielded line than for an unshielded line.

An earth wire installed underneath the conductors as part of the system protection will have a similar but reduced effect to that of a shield wire above the conductors.

3.7.2 RESULTS OF INDIRECT LIGHTNING STRIKES

The voltage induced in a phase conductor by an indirect strike on a typical unshielded distribution line has a maximum value of about 250kV. This implies that the basic insulation level of a line in an area of high lightning incidence should be more than this level, otherwise flashovers (as explained in the next Part) would occur. The attenuation of the induced voltage is low and structures several kilometres away may be affected; flashovers occurring because of lower insulation level on another structure or because of voltage reinforcement due to reflection at a spur line or end of line structure.

An overhead shield wire will reduce the amplitude of the induced surges by only 10% to 20%. This is not significant in terms of insulation levels of the order of 300kV. Insulation levels on shielded lines are thus designed to withstand induced surges of the same magnitude as for unshielded lines.

3.7.3 FLASHOVERS AND THE DEVELOPMENT OF POWER-FREQUENCY ARCS

Impulse breakdown flashover across an air path (for example across an insulator to earth) will tend to develop into a power-frequency arc, which will cause a power outage. An impulse breakdown across a wood path will not tend to develop into a power-frequency arc because of the arc-quenching properties of the wood path (Eskom, 1989). Careful co-ordination of insulation on a woodpole structure, so that the arc-quenching properties of the wood path are utilised, will reduce the occurrence of power-frequency arcs and hence of outages.

The higher the pole footing resistance the lower the arc current and the higher the residual voltage on the conductors. The chance of a flashover occurring at adjacent poles and of a power-frequency arc developing is higher for a higher residual voltage.

The probability of flashover damage to the pole increases as the insulation level increases (that is, as the length of the wood path increases) and if the footing resistance is low. As the insulation withstand level reaches the 1 to 2 MV level (for a full pole length) the number of structures flashing over as the result of a direct strike decreases and the flashover discharge current increases. The surge severity and possibility of damage to equipment also increases.

Spark gaps offer low cost overvoltage protection in areas of low lightning incidence (ground flash intensity < 1 per km² per year). However, the resulting power-frequency arc has to be cleared by protective switchgear. Frequent spark gap operation and hence the frequent operation of protective switchgear would be unacceptable in areas of high lightning intensity. In these areas surge arresters are used.

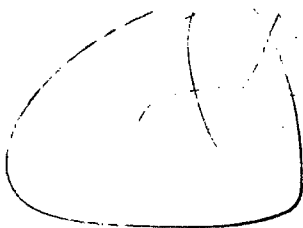
However, on a long line with few loads, in an area of low lightning intensity, it may also be better to select a high withstand voltage with effective surge protection at all equipment installations.

On a line with closely-spaced loads a lower insulation withstand level will permit flashovers. The residual voltage and hence the stress on the connected equipment will be reduced.

3.7.4 IMPULSE WITHSTAND LEVEL OF A STRUCTURE

The minimum insulation level that the path from conductor to ground can have is that of the insulator when it is mounted on an earthed spindle. Typical values of line post insulator impulse withstand voltages range from 100kV (11kV insulator) to 150kV (22kV insulator). The maximum insulation level that this path can have is approximately 1MV to 2MV, when there is about 10m of wood path between the insulator spindle and the ground.

An insulation level between these two extremes is obtained by running an earth wire up the pole so that the effective path to earth is shortened. A distance of approximately 0,5m of wood path plus the insulator provides a 300kV basic insulation level (BIL). This is sufficiently above the voltage of 250kV induced in a phase conductor by an indirect strike to limit the occurrence of flashovers. The BIL of 300kV has generally been adopted as a standard by Eskom for use in areas of high lightning intensity. (Eskom, 1989a)



3.7.5 POLETOP STRUCTURE HARDWARE USED TO LIMIT LIGHTNING EFFECTS OR DAMAGE

The additional hardware required for the establishing of a 300kV BIL is only the earth wire and staples. Many examples of structures "earthed" in this manner are shown in Section 2.1 (on South African practice) of Chapter 2. The provision of fully-earthed and bonded structures such as shown in Figure 2.02 require hardware for bonding the insulator spindles together and to the earth wire. This Figure also illustrates a choice of fittings that go around, rather than through the wood. This means of securing the crossarm to the pole will eliminate splitting of the pole at a through bolt due to a lightning strike.

Choice of the wood type will influence the effectiveness of the design. Eucalyptus cloeziana (75MPa rupture capacity) appears to be better than eucalyptus saligna (55MPa). (Sadurski, et al., 1989)

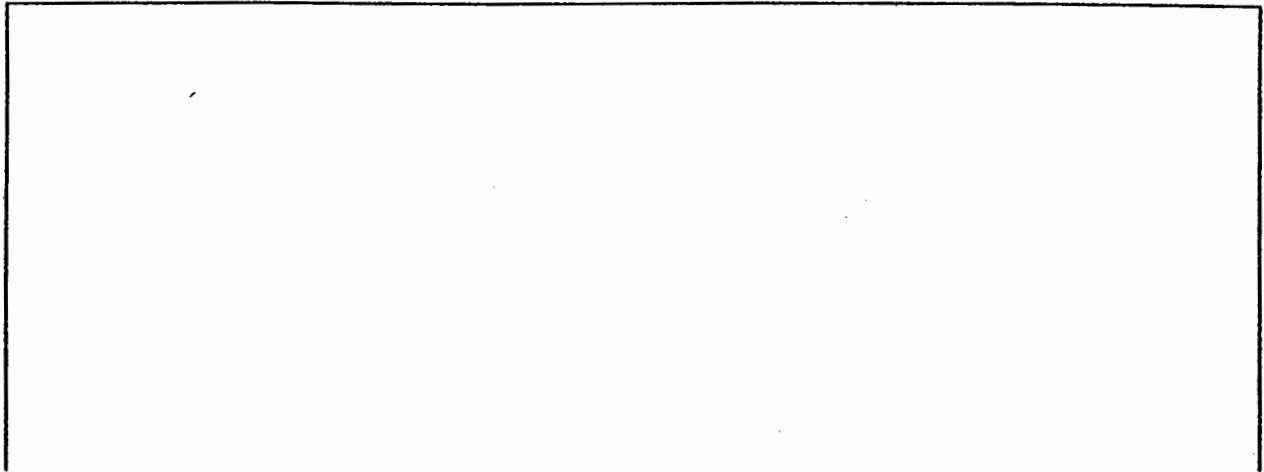
Figure 3.06 details the various alternatives for bonding or earthing and what the resultant effects of direct or indirect lightning strikes may be. This chart can be used as a guide to the consequences of design decisions.

Further factors which will influence the choice of insulation level or of fittings include:

- Lightning intensity
- Lightning surge arrester types and ratings (for handling line surges)
- Line lengths and equipment counts
- Desired or permitted outage rates or required security of supply.

Current practice within Eskom is to use only two of the five alternatives as set out in Figure 3.06. A basic insulation level of 300kV is used in areas of high lightning intensity and no bonding or earthing is used in areas of low lightning intensity. The fact that the A-frame steel crossarm, as used in the coastal Cape areas, bonds the spindles is not relevant to lightning performance but coincidental to its material of manufacture.

All five alternatives are evaluated and compared in Chapter 4, where eight selected South African poletop configurations are analysed.



	spindles bonded		spindles not bonded		spindles bonded and earthed
	short gap	full pole gap	short gap	full pole gap	
Arc Quench Gap	short gap	full pole gap	short gap	full pole gap	---
Insulation Levels: Phase to Phase	2 X Insulator		2 x insulator + gap		2 X insulator
Insulation Levels: Phase to Earth	300kV	1MV	300kV	1MV	1 x insulator
Effect of Induced Surges	induced flashover surges unlikely				probability of flashover to earth
Effect of Direct Strikes	high probability of phase to phase fault followed by power arc possibility of high amplitude surges along line		phase to phase and phase to earth flashovers likely	possibility of high amplitude surges along line	high probability of flashover to earth at several structures

Based on information in Gaunt, Britten & Geldenhuys (1989)

INSULATION CO-ORDINATION ALTERNATIVES

FIGURE 3.06

Field studies are being used to evaluate comparative insulation co-ordination philosophies (Sadurski, et al., 1989). Indications are that the use of a 300kV BIL is proving to be the most effective in high lightning areas. In the areas of low lightning intensity, such as the Cape coastal areas, no special precautions need be taken with regard to the poletop structure.

The line is only part of the rural distribution network which includes feeder and consumer substations. The lightning performance of the total network has to be considered. Provision of spark gaps, protective switchgear and/or surge arresters forms part of this overall system performance co-ordination. All of these last-mentioned items are, however, outside the scope of this thesis.

The use of concrete poles on rural feeders will, however, change practices considerably. A structure using a concrete pole has to be of a "fully bonded and earthed" construction because of the internal reinforcing of the concrete pole.

3.8 FORMULAE FOR THE CALCULATION OF VOLT DROP AND ELECTRICAL LOSSES

This Section examines the electrical losses which occur in a rural distribution line. The ultimate aim is to obtain formulae which relate such losses to the geometric configuration of the conductors on the poletop structure. The formulae will then be used for the analysis of South African practice in Chapter 4.

The purpose of a distribution line is to transfer electrical power at a selected voltage. The voltage at the receiving end of the line should be within the prescribed limits of the nominal line voltage. (Limits of $\pm 5\%$ are used for planning purposes within Eskom (Lay, 1990).) The line losses have two effects, they are effectively lost revenue and they cause heating of the line. The loss in revenue forms part of the economic equation for the line: $\text{return} = \text{income} - \text{costs} - \text{losses}$. Heating of the conductor by the current it carries is a factor in the determination of the operating temperature of the line. The operating temperature of the conductor affects sag and therefore clearances and also affects the operating life of the conductor (due to metallurgical effects).

This Section is divided into four Parts. The first Part gives a brief outline of the electrical design process with examples of calculations. The second Part discusses the thermal operating limit of a distribution line.

The third Part details the factors that influence the power-carrying capacity of the line. These factors are: resistance, inductance and capacitance. They are in turn functions of the length of the line, the conductor type and the geometry of the configuration.

The fourth Part of this Section combines the factors detailed in the third Part into formulae which relate the losses of the line to these factors and to the geometric parameters of the line.

3.8.1 AN OUTLINE OF A PROCEDURE USED FOR DESIGNING THE ELECTRICAL ASPECTS OF A RURAL DISTRIBUTION LINE

An 11kV or 22kV rural distribution line in South Africa could range in length from a few kilometres up to about 80 kilometres. The design load would be between about 300kVA and 5MVA. The most commonly-used conductors for rural lines are Fox, Mink and Hare ACSR conductors with a 6/1 aluminium/steel stranding.

The simplified design process is best illustrated by means of the example below. The formulae used will be explained in more detail at a later stage.

Example: The design of a rural distribution line.

It is required to supply a three-phase load of 4MVA over a distance of 10km. The initial assumption is that the system voltage will be 11kV and the conductor will be ACSR Mink. (Resistance/km (R) = 0,45 ohms/km; Reactance/km (X) = 0,42 ohms/km)

The power factor (cos a) at the receiving end (at the load) is 0,9 lagging. V_s (sending end voltage) is at +5% and V_r (receiving end voltage) should be no lower than -5% of the system voltage.

The current (I) in the conductor is 210A at 11kV and 105A at 22kV for the 4MVA load. The maximum allowed volt drop is 10% ($V_s - V_r$) or 1,1kV at 11kV and 2,2kV at 22kV.

Mink conductor at 11kV:

$$I^2R \text{ losses: } = 210^2 \times 0,45 \times 10 = 198\text{kW}$$

$$\text{Volt Drop: } IR\cos a + IX\sin a \text{ (approx.)}$$

Equation 3.30

$$= 210 \times 0,45 \times 10 \times 0,9 + 210 \times 0,42 \times 10 \times 0,44$$

$$= 850 + 388 = 1\,238\text{V phase} = 2\,144\text{V line}$$

This volt drop is too high, try a 22kV line voltage.

The current of 210A is well below the rated current (260A) of the conductor for 75°C. (Figure 3.07)

Mink conductor at 22kV:

$$I^2R \text{ losses: } 1052 \times 0,45 \times 10 = 49\text{kW}$$

$$\text{Volt Drop: } IR\cos a + IX\sin a$$

$$= 105 \times 0,45 \times 10 \times 0,9 + 105 \times 0,42 \times 10 \times 0,44$$

$$= 425 + 194 = 619\text{V phase} = 1.072\text{V line}$$

This volt drop is within the limits of 2 200V at 22kV. The line could be extended by a further 10,5km for the same load (at the end) without exceeding the volt drop limit. ($2\ 200 \times 10/1\ 072 = 20,5\text{km}$)

The cost of the line losses (assuming an average of half the losses per day) is given by:

$$\text{kW} \times \text{hours} \times \text{days} \times \text{rate} = 24,5 \times 24 \times 365 \times 0,145 = \text{R}31\ 120 \text{ per year}$$

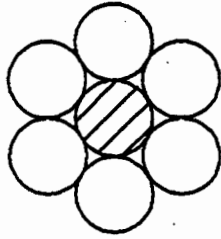
$$(\text{rate: } 14,5\text{c/kWh (Eskom, 1990)})$$

which is a quarter of that at 11kV.

A parameter called a megawatt-kilometre (MW-km) is useful in determining the capacity of a line as a function of volt drop. From the above example, the 22kV Mink line will carry 4MVA at 0,9 p.f. lagging over a distance of 20,5km within the voltage limits of $\pm 5\%$.

$$\text{The MW-km limit for this line is given by: } 4 \times 0,9 \times 20,5 = 74\text{MW-km}$$

None of the calculations or information used above includes any reference to the geometric configuration of the conductors. Other, more detailed, formulae are detailed in Part 3.8.3. The above Part is intended only as a brief outline.



6 ALUMINIUM / 1 STEEL

CODE NAME	EQUIV. COPPER AREA mm ²	STRANDING and WIRE DIAMETER mm	DIAM. OVER STEEL mm	OVER-ALL DIAM. mm	Al AREA mm ²	STEEL AREA mm ²	TOTAL AREA mm ²	MASS kg/km			ULTIMATE TENSILE STRENGTH N	BREAKING LOAD kg	COEFF. LINEAR EXPAN. /°C x 10 ⁻⁶	INITIAL MODULUS ELASTIC N/mm ²	FINAL MODULUS ELASTIC N/mm ²	DC RESIST @20°C ohms/km	75°C CURRENT RATING amps	CURRENT DENSITY amps/cm ²
								Al	STEEL	TOTAL								
FOX	22,52	6/1/2,79	2,79	8,37	36,68	6,11	42,80	101	48,10	149	13100	1340	19,31	50700	80400	0,7822	190	518
MINK	38,71	6/1/3,66	3,66	10,98	63,13	10,52	73,65	174	82,80	257	21900	2230	19,31	49100	80400	0,4546	260	412
HARE	64,52	6/1/4,72	4,72	14,16	104,98	17,50	122,48	289	138	427	36000	3670	19,31	48500	80400	0,2733	360	343

Extracts from: Aberdare (1990)

OVERHEAD ALUMINIUM CONDUCTOR, STEEL REINFORCED (ACSR) : BRITISH STANDARD SIZES

FIGURE 3.07

3.8.2 THE THERMAL OPERATING LIMIT OF THE LINE

The information contained in this Part is included partly for reference and partly to explain the importance of the temperature limit of the line.

The longer rural distribution lines at 11kV and 22kV are not operated near their thermal limits. They are limited in the amount of power they can transfer by the volt drop of the line, as was illustrated by the example in the previous Part.

The temperature of the conductor is of importance for several reasons.

Firstly, the line is built for a certain predetermined sag which depends on the erection tension and temperature of the conductor for which the line was designed. The sag of the conductor will primarily depend on its temperature once it is operating. Consequently the legal and safety clearances also vary as a result of temperature changes.

Secondly, operating an aluminium conductor at a high temperature (100°C and over) for extended periods has the effect of reducing the strength of the conductor. The effect is additive in that the conductor does not recover from over-temperature operation. A loss of 10% of conductor ultimate tensile strength over the life of the conductor is accepted as a world-wide practice (Nolasco, 1989). Distribution lines sometimes need to be operated at higher load currents (and therefore at higher temperatures) for short periods during abnormal conditions of power flow.

The current-carrying thermal limit of the line depends on the steady-state conditions of wind velocity, ambient temperature, solar radiation and electric current. A balance between the heat generated in the conductor and the heat dissipated determines what the ultimate current-carrying capacity of the line may be. The manufacturers supply data on their overhead conductors (see Figure 3.07). This data includes the current ratings of the conductors for operation at a specific temperature and under specified ambient conditions of sun and wind. The designer can then use this data to design the line from the aspect of operating temperature.

3.8.3 FACTORS INFLUENCING THE LOSS PARAMETERS

The following facts are evident from a consideration of formulae used in the example in Part 3.8.1:

For the same current the power loss is dependent on only the resistance (R) of the line whereas the voltage drop is dependant on both the resistance (R) and the reactance (X) of the line.

The reactance (inductive and capacitive) of a three-phase overhead line depends on the diameter of the conductor on the stranding (number of strands), and on the physical spacing (poletop geometry) of the conductors.

INDUCTANCE

The average total inductance per phase of a three-phase fully-transposed line is given by Freeman (1974):

$$L = L_i + 0,2 \ln(c_e/r) \quad \text{mH/km} \qquad \text{Equation 3.31}$$

where:

L_i is the internal inductance of the conductor

r is the radius of the conductor (m)

c_e is the effective spacing (m) $c_e = (c_1 c_2 c_3)^{1/3}$

(c_1, c_2, c_3 are the individual spacings between the conductors.)

The internal inductance of the conductor is a function of the material (magnetic or non-magnetic) and of the stranding. For a solid conductor made of non-magnetic material the internal inductance (L_i) is 0,05 mH/km (Freeman, 1974). A stranded conductor with a large number of strands approximates to a solid conductor and therefore has a similar value for L_i . For steel-cored conductors L_i depends on the relative permeability, which in turn varies with current. (See Figure 3.08)

CHANGE OF INTERNAL INDUCTANCE WITH STRANDING

AAC CONDUCTOR	
strands	internal inductance mH/km
3	0,078
7	0,064
19	0,056
37	0,053
61	0,052
81	0,051
127	0,051

ACSR CONDUCTOR		
strands		internal inductance mH/km
aluminium	steel	
6	1	0,055 + 0,00068 μ
6	7	0,054 + 0,00053 μ
7	7	0,049 + 0,00070 μ
12	7	0,034 + 0,00025 μ
26	7	0,044 + 0,00011 μ
30	7	0,040 + 0,00010 μ
54	7	0,044 + 0,00012 μ

μ : permeability

Based on information given in Butterworth (1954)

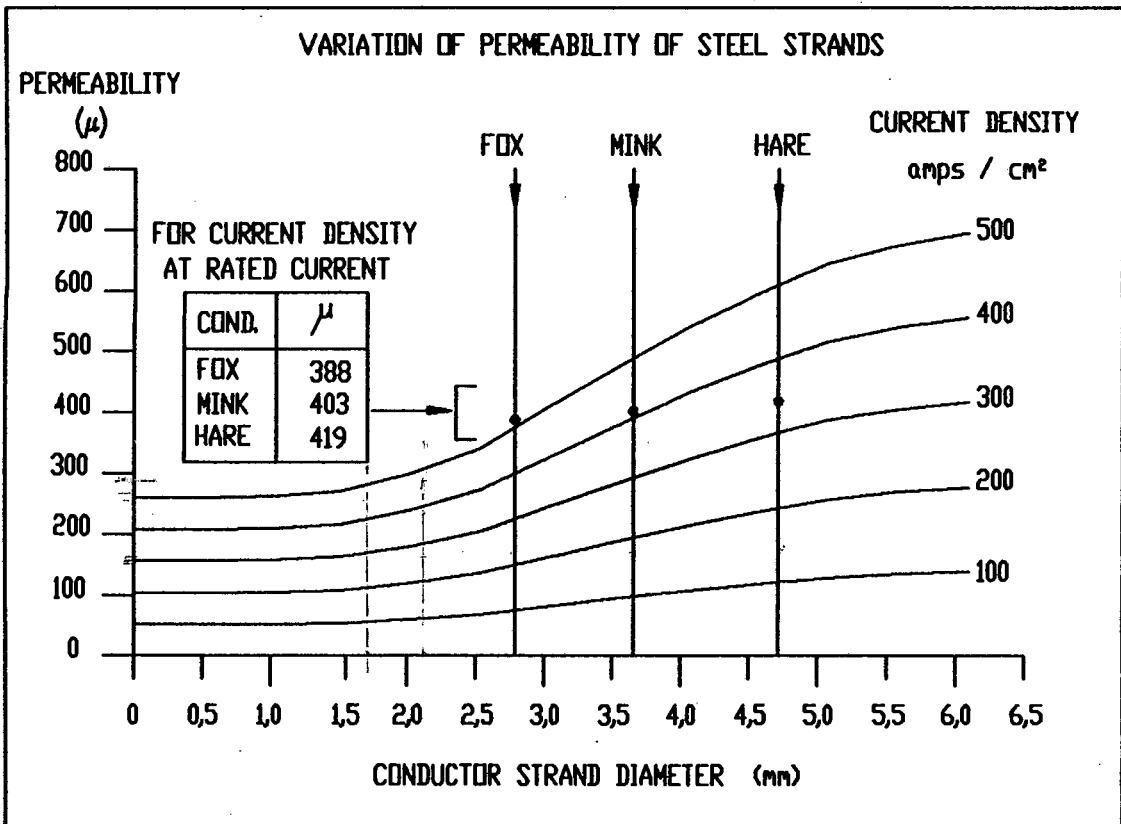


FIGURE 3.08

Examples:

A poletop structure has a geometric mean conductor spacing of 0,9m. The conductor to be used is either Mink (ACSR) or Bluebottle (AAC). Both have 7 strands and an overall diameter of 10,98mm. The permeability for Mink is 403 at rated current.

$$L = L_i + 0,2 \ln(c_g/r) \quad \text{⌘} \quad \text{(Equation 3.31)}$$

geometric mean spacing (c_g) = 0,9m radius of conductor (r) = 0,0055m

Internal inductance (L_i) for: (from Figure 3.08)

Bluebottle conductor = 0,064 mH/km

Mink conductor = 0,055 + 0,00068 X 403 = 0,329 mH/km

Inductance (L): L = 1,08mH/km (Bluebottle) L = 1,35mH/km (Mink)

CAPACITANCE

The average capacitance per phase for a three-phase fully-transposed line is given by Freeman (1974):

$$C = (18 \ln(c_g/r))^{-1} \text{ microfarad/km} \quad \text{Equation 3.32}$$

where c_g and r denote the same variables and units as for inductance.

Example:

For the same configuration as in the previous example, using Mink conductor, the total capacitance is given by: $C = (18 \ln(c_g/r))^{-1}$ (Equation 3.32)

Capacitance (C) = 0,0109 microfarad/km

CALCULATION OF VOLT DROP FOR A "LONG LINE"

For a line longer than about 16km (described as a "long line") the effects of capacitance currents should be taken into account.

A formula for the calculation of volt drop for a long line has been derived from "nominal T method" examples in Freeman (1974). The equivalent circuit diagram and the phasor diagram are shown in Figure 3.09.

$$\text{volt drop (phase voltage)} = (R/2 + jX_L/2)(2I_R + \{j[V_R + I_R(R/2 + jX_L/2)]\}/X_C)$$

Equation 3.33

where:

R is the resistance of one conductor (ohms)

X_L is the inductive reactance (ohms)

X_C is the capacitive reactance (ohms)

I_R is the receiving end current (amps)

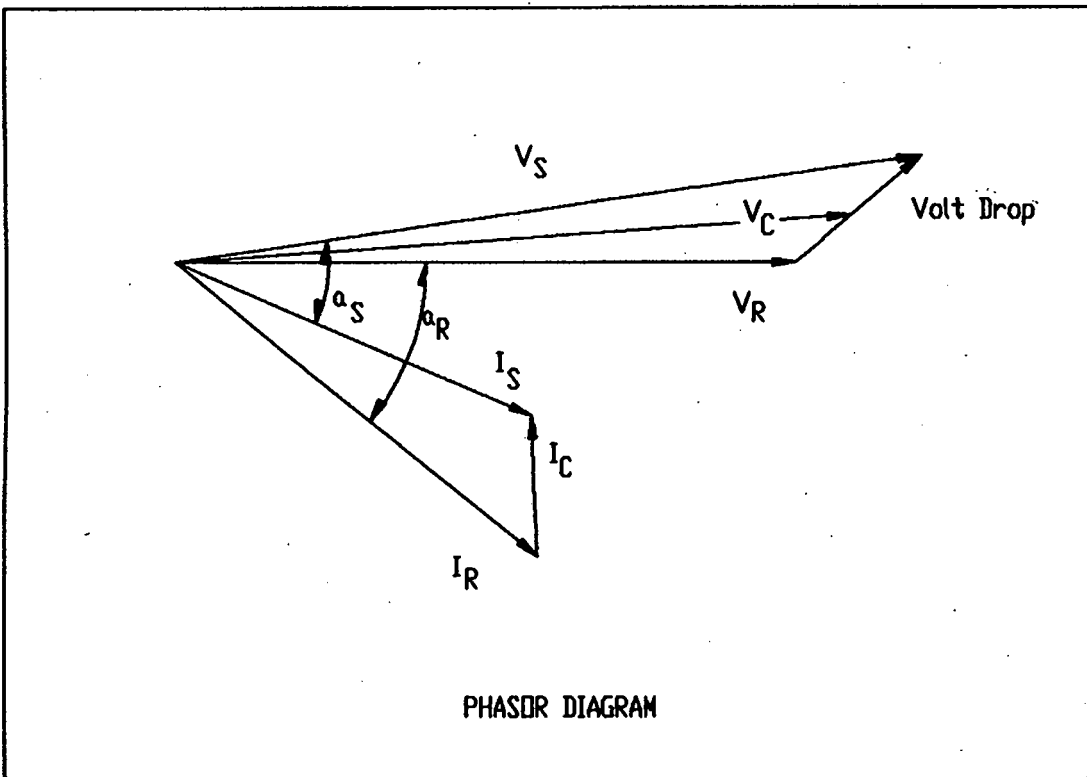
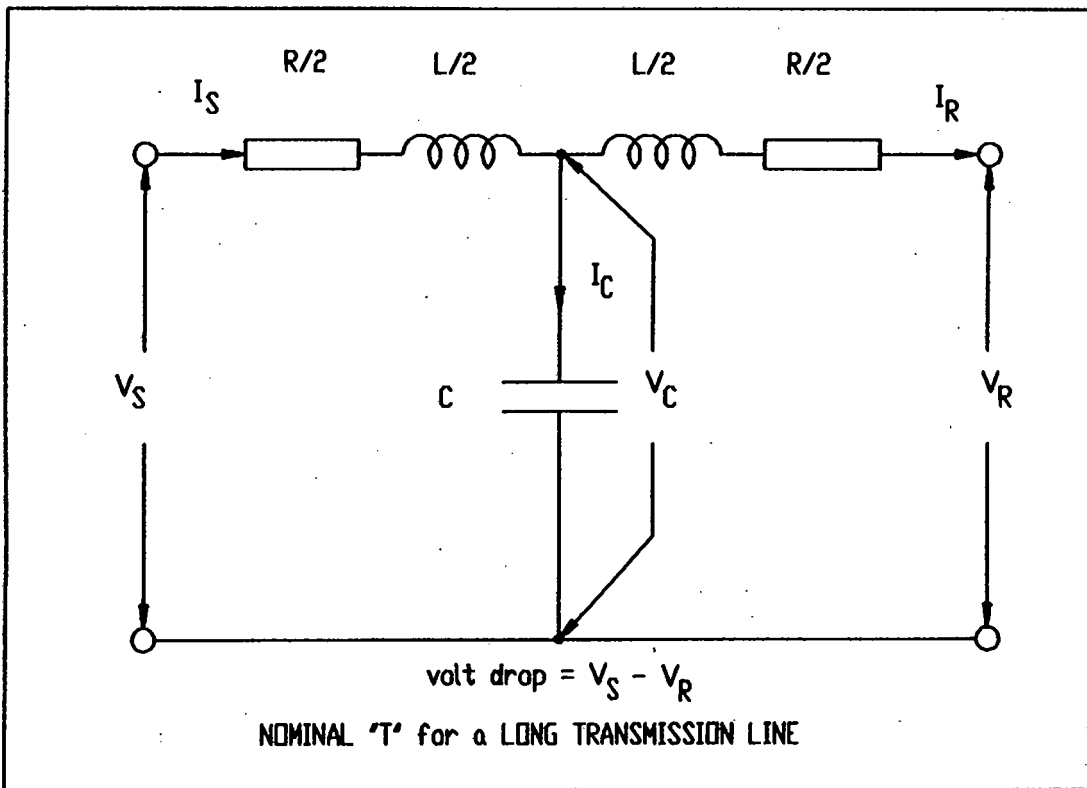
$$I_R = I_R \cos a_R - jI_R \sin a_R$$

V_R is the receiving end phase voltage (volts)

$$V_R = V_R$$

a_R is the angle between I_R and V_R , with V_R as reference

($\cos a_R$ being the power factor of the load)



Source: Freeman (1974)

EQUIVALENT CIRCUIT AND PHASOR DIAGRAM FOR A LONG TRANSMISSION LINE

FIGURE 3.09

3.8.4 COMPARISON OF FORMULAE FOR THE CALCULATION OF THE VOLT DROP OF A DISTRIBUTION LINE

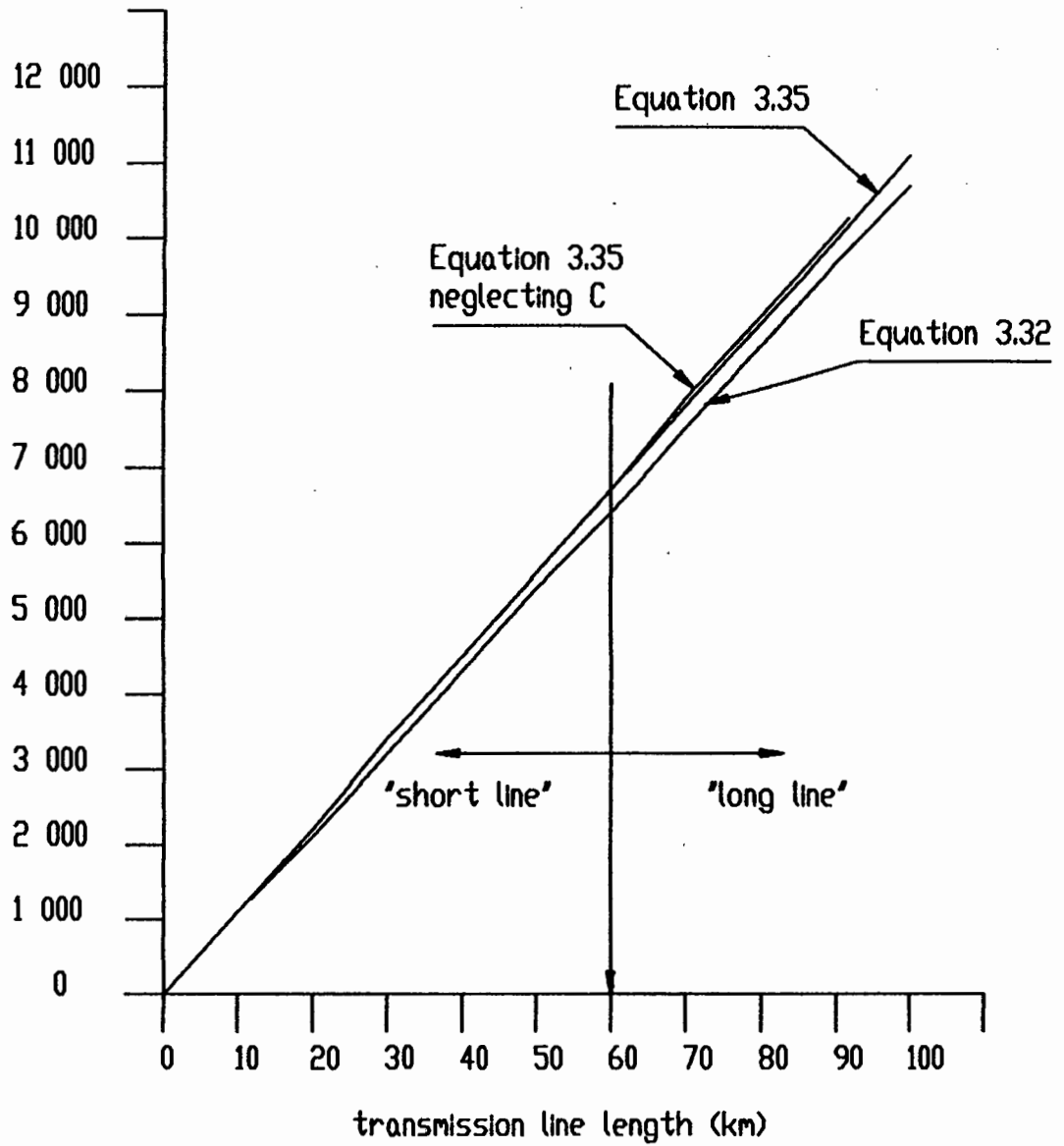
Two equations to calculate the volt drop of a transmission line have been detailed in this Section: Equations 3.30 and 3.33. They have been used to calculate the values for the graphs in Figure 3.10. Equation 3.33 was used twice, once including the effect of the capacitance of the line and once neglecting the capacitance. The calculations were carried out for Mink conductor for a load current of 105 amps at 0,9 lagging power factor.

The graphs illustrate clearly the distinction between a "short line" and a "long line". The effect of including the capacitance in the calculations is evident for line lengths longer than 60km. (This is in contrast to Freeman (1974) who uses a figure of 16km. Glover & Sarma (1987) use a figure of 80km for a 60Hz line.) The error between Equation 3.30 and Equation 3.33 is of the order of 4% for a 60km line and decreases to 3% for longer lines.

The distinction between "long" and "short" lines is somewhat historical. The need for simplifying the formula was to make the calculation easier. This restriction is no longer necessary as a pocket calculator can now be used to solve the complete formula without approximations.

Equation 3.33 has been used for the comparison calculations carried out for the analysis of South African practice in the next Chapter.

volt drop (volts)



CALCULATED VOLT DROP USING THREE DIFFERENT EQUATIONS

FIGURE 3.10

3.9 THE EFFECT OF RURAL LINES ON THE ENVIRONMENT AND ON WILDLIFE

The effect that overhead distribution lines may have on the environment in general is receiving more and more attention worldwide and within Eskom. These lines and structures affect the environment in three ways. The terrain and plant life will be damaged during the construction of the line and during the subsequent operating life of the line unless adequate measures are taken to minimise these effects. The presence of these lines and structures will also have an effect on the wildlife, particularly on birds. The structures clutter up and spoil the view in the countryside, towns and cities.

3.9.1 THE EFFECT OF RURAL DISTRIBUTION LINE STRUCTURES ON THE ECOLOGY

The possible high visibility of the structures crossing open country is not so serious at the lower distribution voltages (11kV and 22kV) as the structures are lower and not as obtrusive. A woodpole distribution line is even less conspicuous in regions where there are trees of comparable height. It is sometimes feasible to site these lines so that they do not stand out against the skyline, where this is made possible by the terrain.

Environmental impact studies are carried out at the design stage of the line. They assess the effect that the line will have on the environment and consequently lead to plans for the restitution of the ecology. The impact studies, if unfavourable, may also result in the line being built on a different route.

A serious problem facing operators and designers of rural distribution lines is the effect that these lines and their peripheral structures are having on wildlife, particularly on birds. Not only do the structures kill birds (mechanically or electrically, that is, by impact or electrocution), but when a short-circuit of some kind is caused there is an interruption to the electricity supply. Neither of these results is particularly serious, regrettable though they may be, unless the line affected is a major supply line or the bird (or animal) an endangered species.

3.9.2 PREVENTION OF WILDLIFE FATALITIES

A method needs to be found which will prevent the unwitting self-destruction of wildlife and the (resulting) interruption of supply. Both goals will then be achieved simultaneously. In general such means are intended to keep the birds away from conductors or earth wires.

Some means, such as large orange spheres fixed to the conductors, are provided so that the birds are made aware of the conductors in order to decrease the incidence of impact during flight. (Eskom, 1988)

The other cause of fatalities and supply interruptions, bird electrocutions, can be eliminated by preventing the bird from bridging the phase-to-phase or phase-to-earth separation, either while perching on the structure or during take-off or landing. This can for example be achieved by making the separation larger ("anti-swan" structures; SECWA (1990)), insulating one of the conductors (flying fox protection; PAWA (1989)), providing an effective barrier and separation by suspending the two outer phases (Eskom, 1988), eliminating possible perches (vertical conductor configuration; Elektron (Nov. 1990)), or providing safe perches (Eskom, 1988).

Other problems, such as insulator pollution caused by bird droppings and nest-building, are not major causes for concern on the lower voltage distribution line intermediate structures. Nest-building would tend to be a bigger problem on peripheral structures such as on pole-mounted transformers or switchgear. Inspections of such peripheral structures and/or preventative measures or designs would alleviate the problems.

It is necessary to modify existing structures where such specific structures, either because of their location or design, are causing fatalities, particularly to endangered species. The bird fatalities should be closely monitored and correctly identified and reported so that cost-effective, specific action can be taken. The "Eskom Bird Identification Guide" by John Ledger (Eskom, 1988) has been produced for this purpose.

CHAPTER 4

ANALYSIS OF SOUTH AFRICAN PRACTICE

The purpose of this Chapter is to analyse the data on, and to discuss the limitations of, eight of the configurations used in South Africa for new rural distribution lines.

It is divided into four Sections. The first Section outlines the reasons for the choice of the eight configurations and provides dimensional and structural details and drawings of these designs. The second Section explains the scope of the analysis and discusses the factors that will be used to analyse and compare the configurations. The third Section covers the analysis and comparison of the configurations and is divided into seven Parts, each covering a separate facet of the analysis. The last Section probes the factors which limit the span and provides graphical means for doing this.

4.1 DETAILS OF SELECTED DESIGNS

Six of the eight Eskom designs for intermediate structures being used for new lines in 1990 were chosen. The two designs not chosen were both special adaptations and therefore not widely used. However, modifications or adaptations to the designs current in Eskom in 1990 were proposed in May 1991, thus adding two further designs to the six originally selected.

The important dimensions for each of the selected designs are given in Figure 4.01. It must be emphasized that there are many dimensional variations of a basic configuration. The six 1990 configurations selected have phase separations which are of the order of one metre.

Different insulator lengths will affect the distances between phases and above ground. These differences are of the order of centimetres and thus do not have a major effect. A representative (cycloaliphatic) insulator with a length of 250mm has been used throughout for all post insulators for the purposes of this analysis.

Detailed drawings showing exploded views of, and a completed structure for, each configuration are given in Figures 4.02 to 4.08.

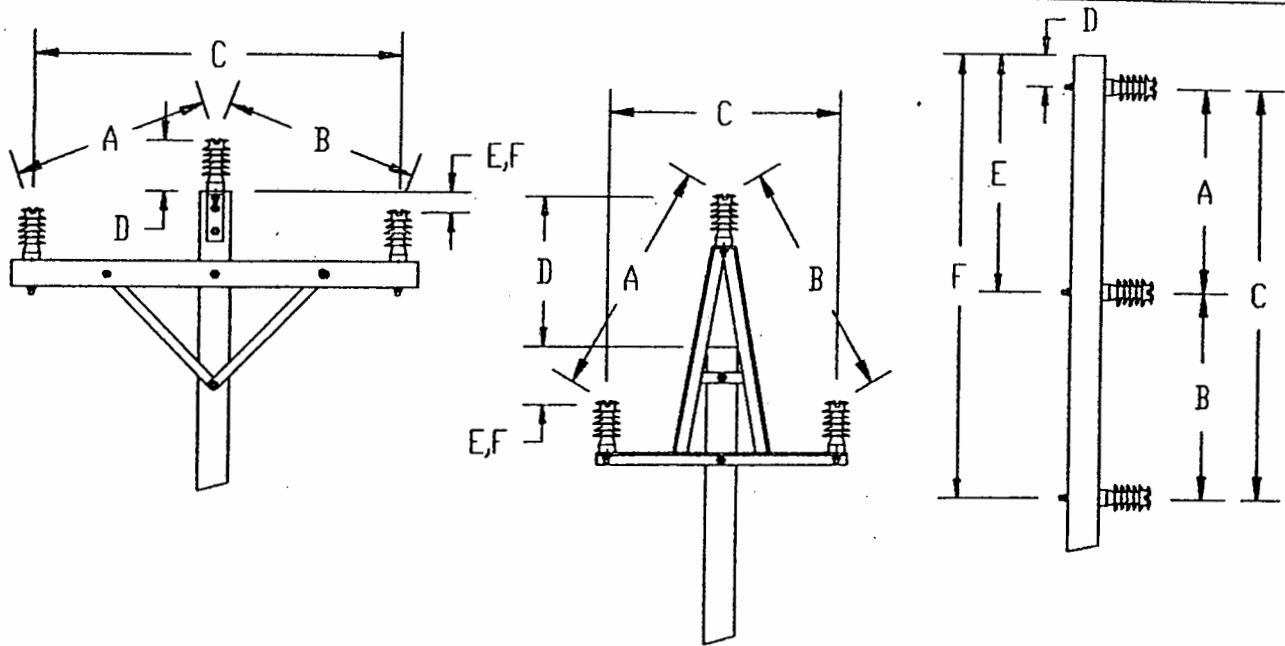
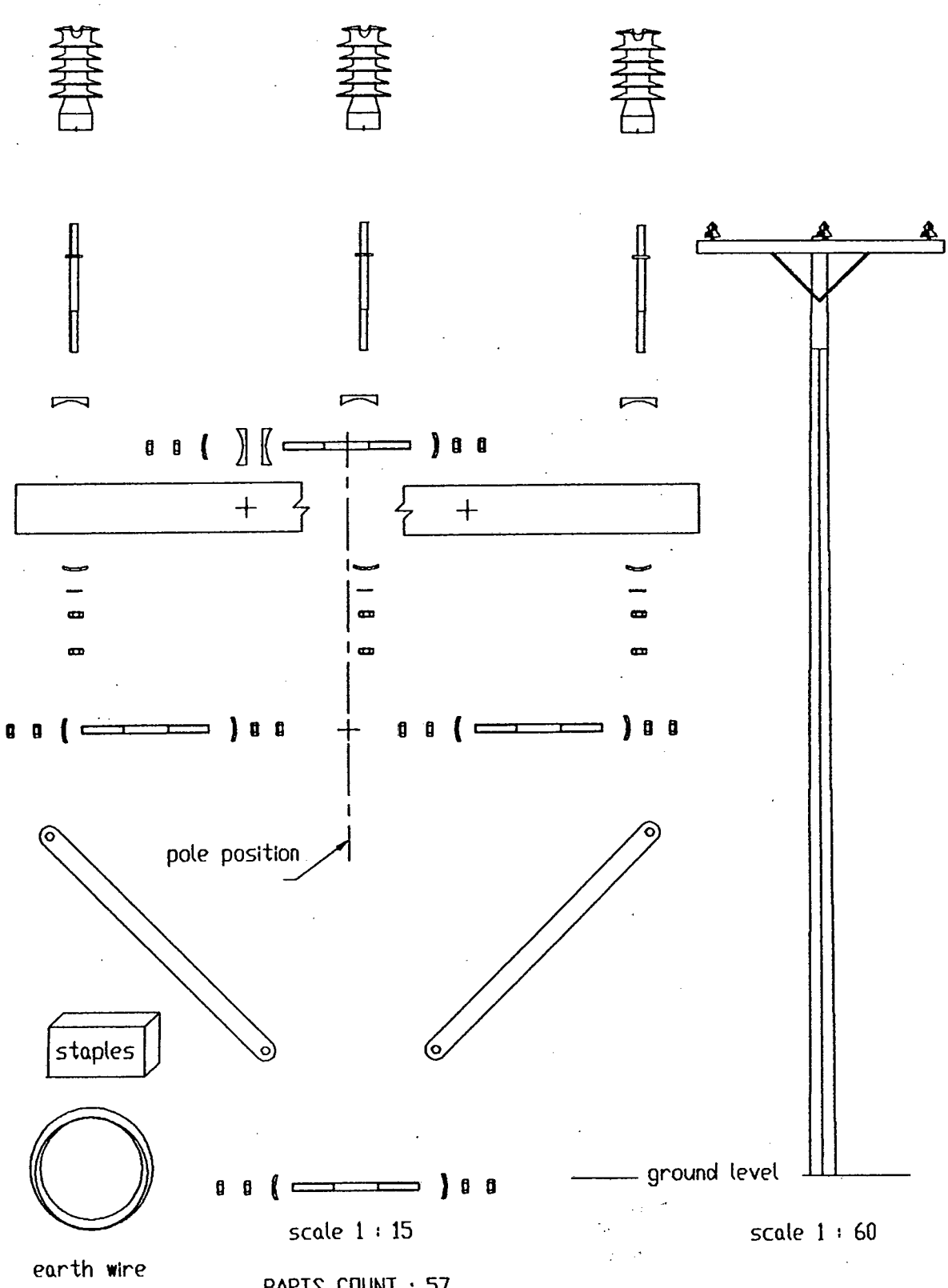


Figure	Configuration	Phase Separation (mm)			above pole top (mm)				Xarm Area m ²
		A	B	C	Conductor Attachment D	E	F	C of G	
4.02	Horizontal	1100	1020	2120	+ 210	+ 210	+ 210	+ 210	0,05
4.03	Vertical Offset	1000	1000	1520	- 150	- 910	-1670	- 910	nil
	New Vert. Offset	877	877	1200	- 200	- 800	-1400	- 800	nil
4.04	Vertical	1000	1000	2000	- 150	-1150	-2150	-1150	nil
4.05	A-frame Delta	1150	1150	1140	+ 750	- 250	- 250	+ 83	0,10
4.06	Horizontal Delta	960	960	1800	+ 250	- 190	- 190	- 93	0,05
4.07	Suspension Delta	1200	1200	1800	+ 250	-1060	-1060	- 623	0,08
4.08	New A-Frame Delta	925	925	1400	+ 270	- 330	- 330	- 130	0,06

- Notes: 1. Certain phase separation, conductor attachment and C of G distances depend on insulator lengths.
 2. Xarm (Crossarm) areas are total effective transverse areas including insulators. The vertical configuration insulators are shielded by the pole.
 3. The average effective area of a pole is 1,8 m².

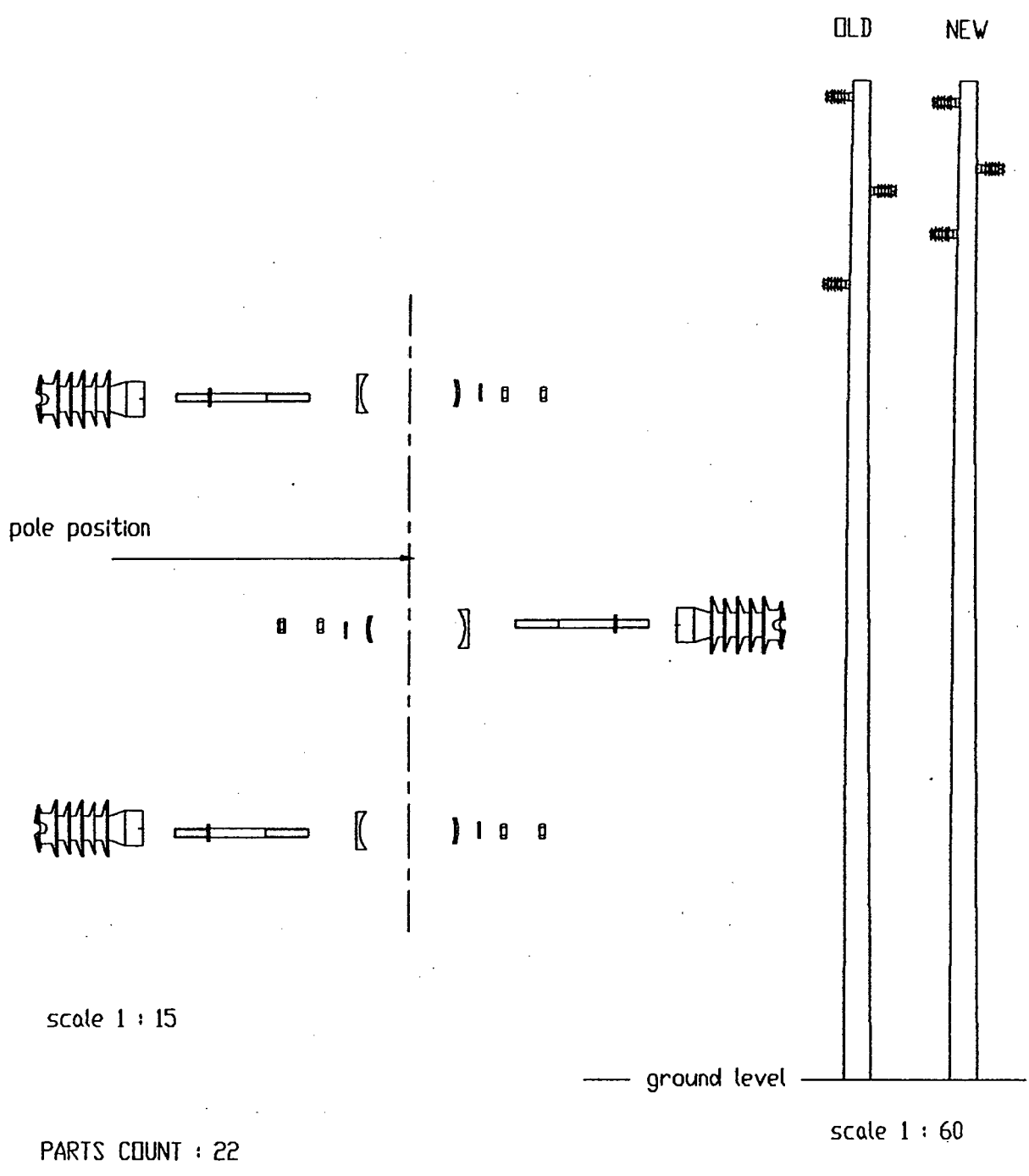
DEFINITION OF TERMS, DETAILED DISTANCES AND AREAS

FIGURE 4.01



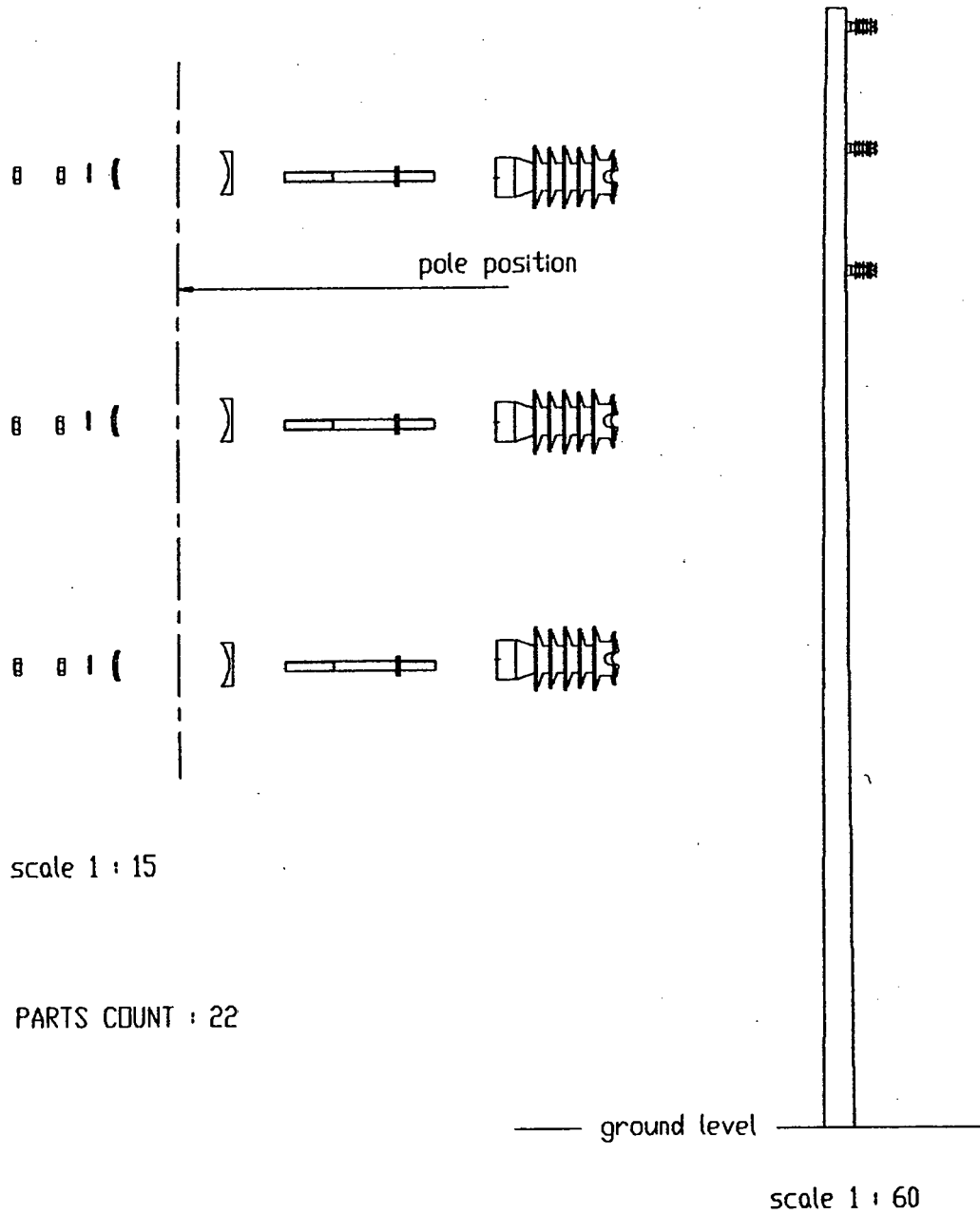
HORIZONTAL CONFIGURATION : EXPLODED VIEW AND PARTS COUNT
 (conductors or conductor ties not shown or counted)

FIGURE 4.02



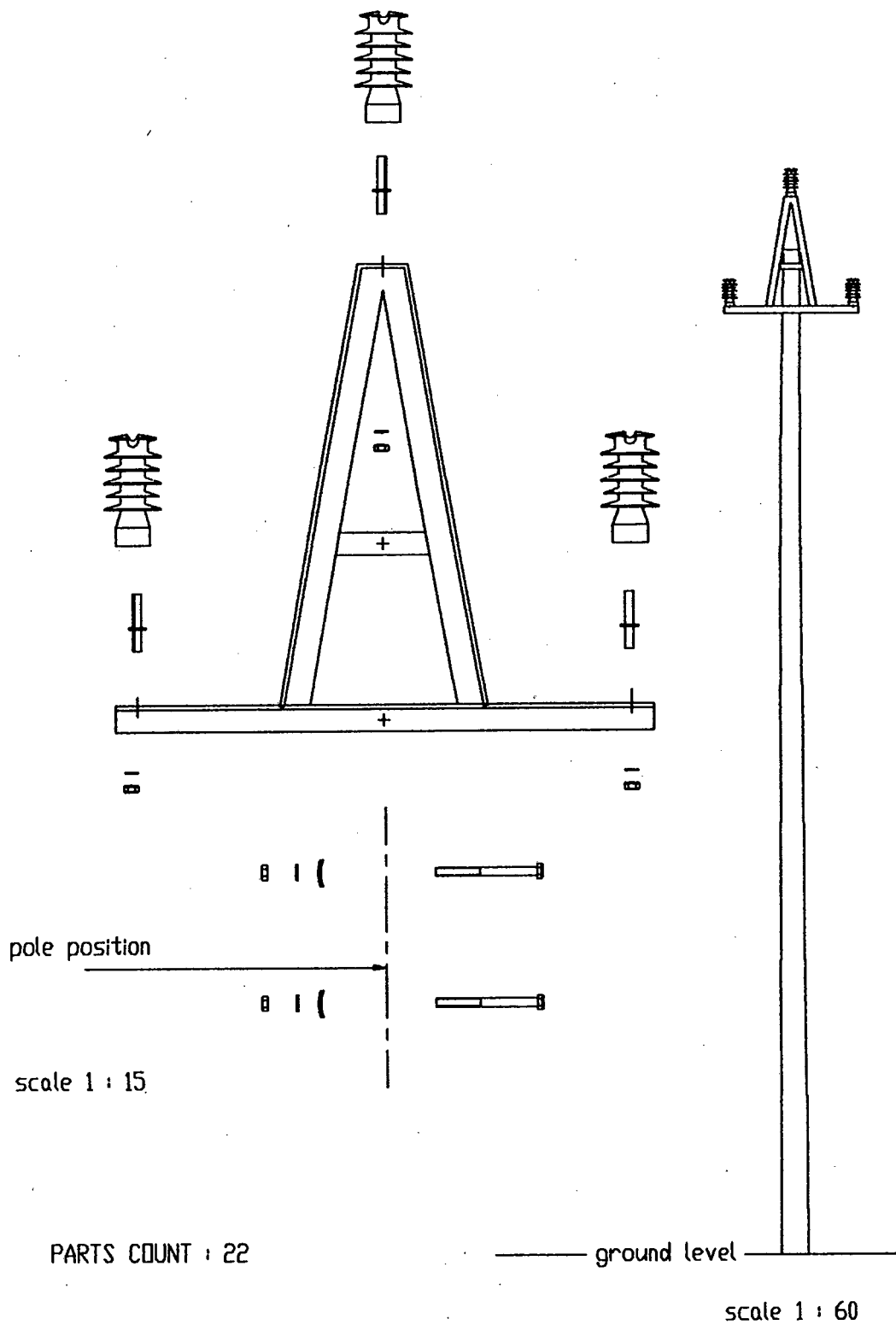
OLD AND NEW VERTICAL OFFSET CONFIGURATION : EXPLODED VIEW AND PARTS COUNT
 (conductors or conductor ties not shown or counted)

FIGURE 4.03



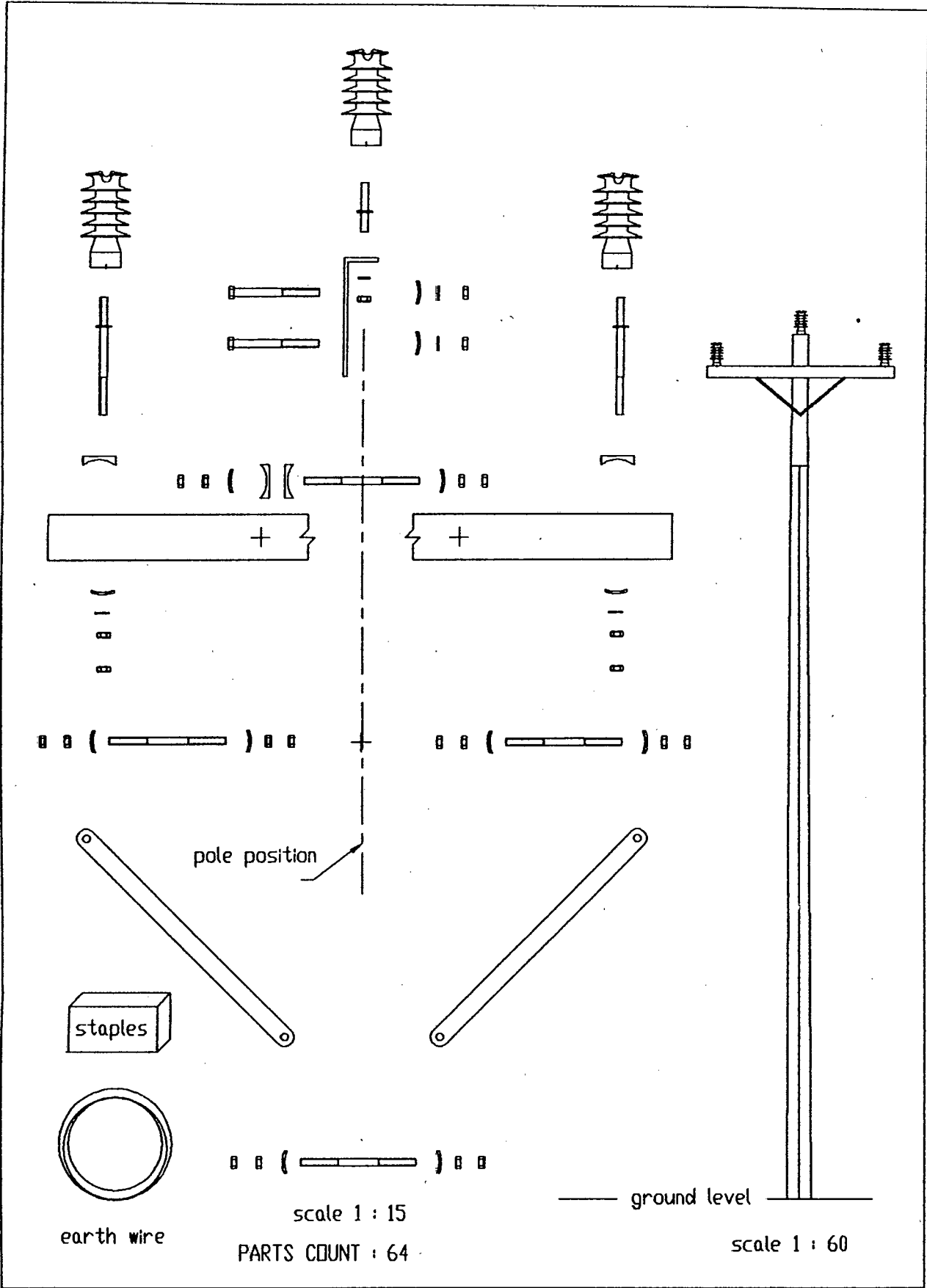
VERTICAL CONFIGURATION : EXPLODED VIEW AND PARTS COUNT
 (conductors or conductor ties not shown or counted)

FIGURE 4.04



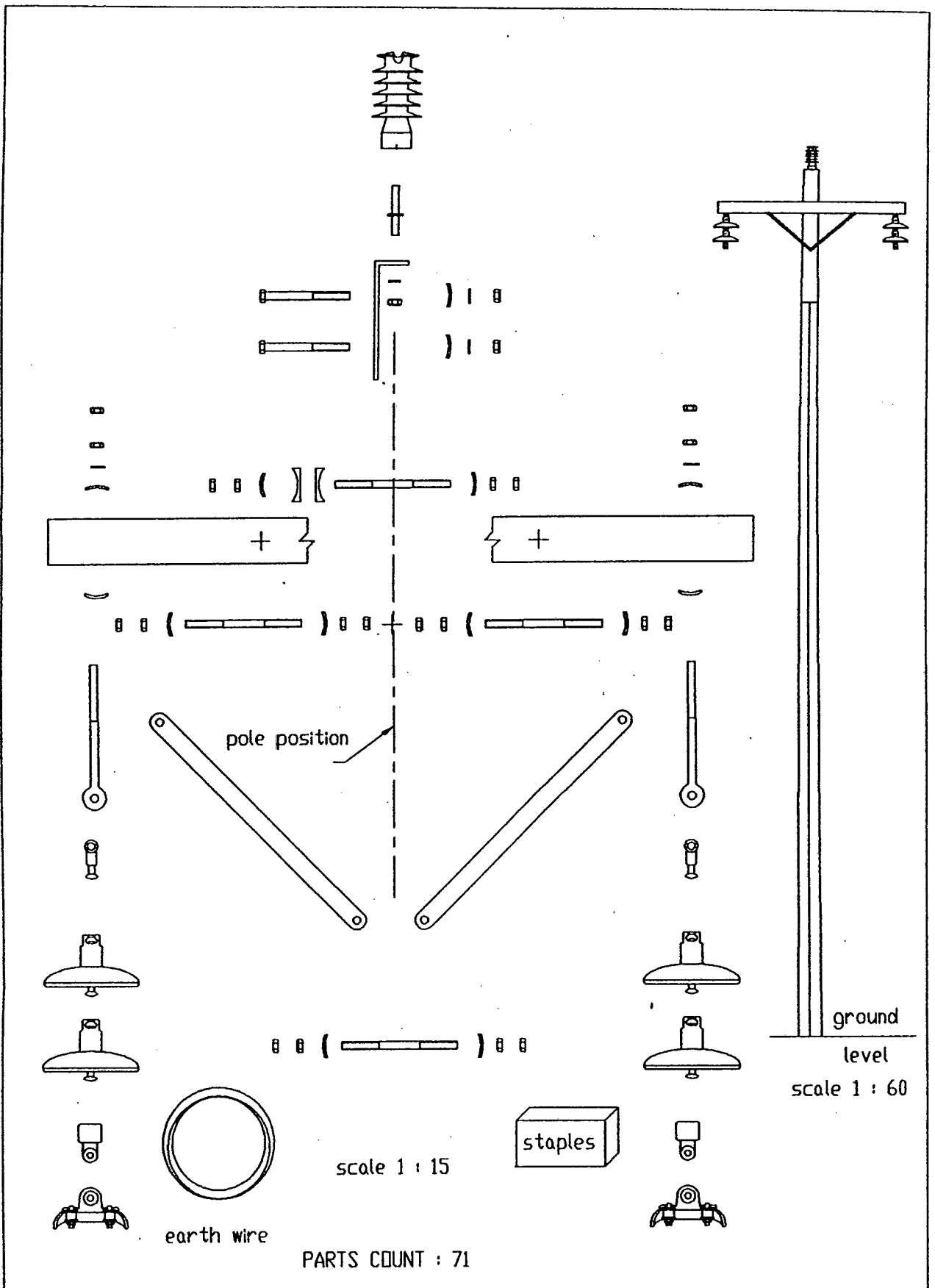
A-FRAME CONFIGURATION : EXPLODED VIEW AND PARTS COUNT
 (conductors or conductor ties not shown or counted)

FIGURE 4.05



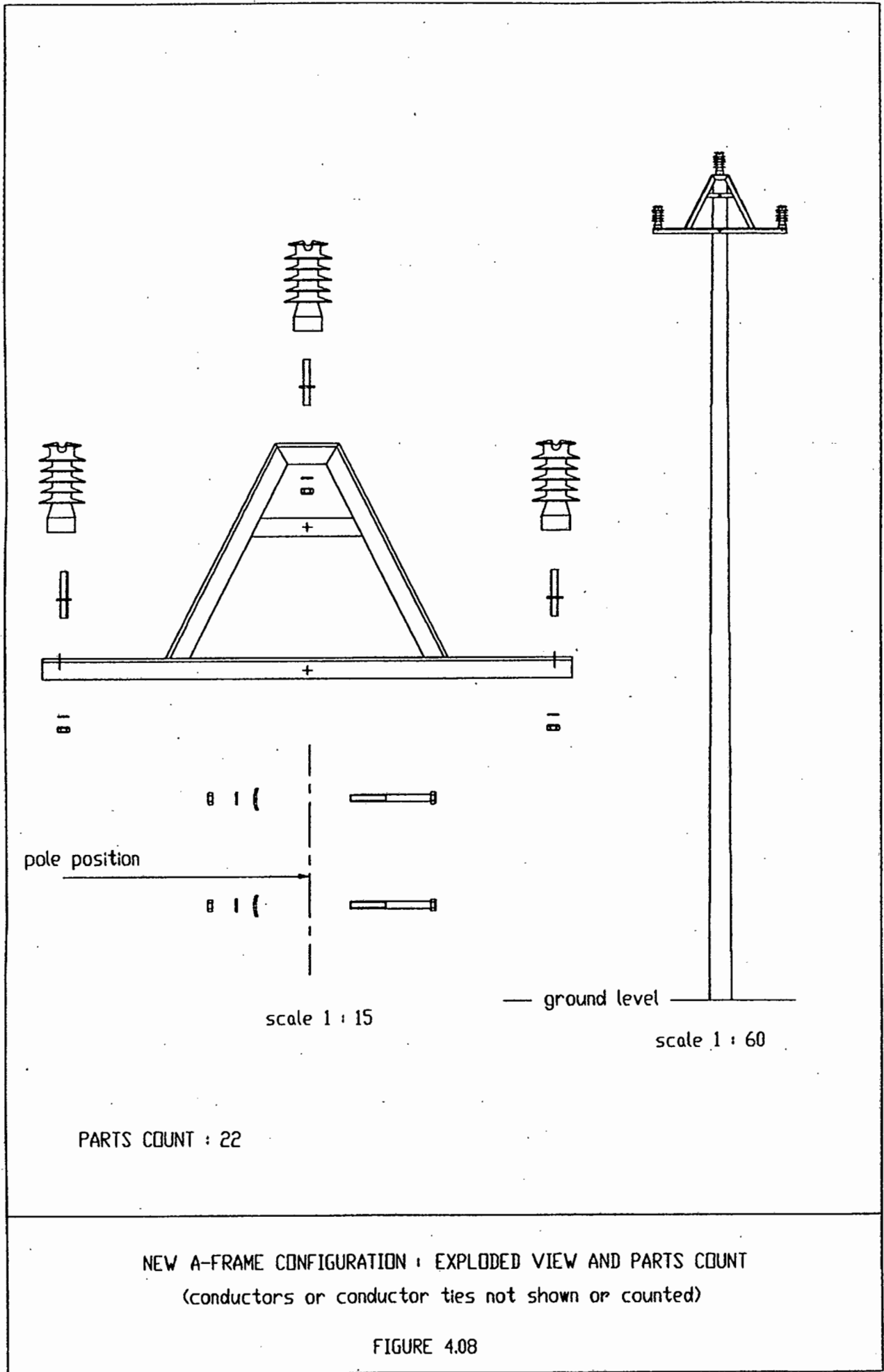
HORIZONTAL DELTA CONFIGURATION : EXPLODED VIEW AND PARTS COUNT
 (conductors or conductor ties not shown or counted)

FIGURE 4.06



SUSPENSION HORIZONTAL DELTA : EXPLODED VIEW AND PARTS COUNT
(conductors or conductor ties not shown or counted)

FIGURE 4.07



4.2 SCOPE OF THE ANALYSIS

The maximum span for which a configuration is suitable is the common factor in the comparison of the various designs. How this common factor is used is detailed below. The reason for utilising the longest span possible is simply one of cost; the longer the span, the fewer structures are needed for a given length of line and thus the lower the total cost per kilometre.

This statement is valid only if the savings obtained by having fewer structures is greater than the cost of the stronger or taller structures required because of the longer spans.

It has been assumed, for the purpose of these comparisons, that the line has been erected on level ground and that all the spans are equal.

Four of the seven factors used in the analysis can be related directly to the span (the distance between two adjacent poles) as a limiting factor. The maximum permissible span is then a common measure of the limitations of the configurations. These four factors are:

CLEARANCE: The longer the span, the greater the sag and therefore the less the clearance to ground. In terms of the configuration this means that the closer the lowest conductor is to the top of the pole, the longer the span can be.

POLE STRESS: The greater the transverse force applied to the top of the pole, the greater is the stress in the pole at ground level. This transverse force is caused by the wind blowing across the line against the areas of the pole, top structure (crossarm, etc) and conductors. The magnitude of the force depends on the wind pressure and on the size of the areas exposed to the wind. The biggest area exposed to the wind is that of the conductors, which is directly proportional to the span. Also, the higher the conductors are up the pole, the greater is the bending moment and hence the stress in the pole at ground level. The foundation is assumed to be rigid and the full load has thus to be taken by the bending of the pole.

OVERTURNING: This is caused by the same factors as is pole stress, i.e. wind pressure, exposed areas and height up the pole of the application of the forces. In this instance the pole is assumed to be rigid and the full load has to be taken by the foundation. The "foundation"

4.3 ANALYSIS AND COMPARISON OF THE CONFIGURATIONS

In this Section the group of eight selected configurations is subjected in turn to analysis in terms of each of the seven stated factors.

It was decided to use the metricated versions of the formulae from the Code of Practice (SAIEE, 1966) (see Chapter 3) for the required pole stress, foundation and conductor spacing calculations. The reasons are twofold:

Firstly, the use of the SAIEE (1966) formulae should enable the results of the analysis to be compared directly with normal South African (Eskom) practice, which is done according to the same set of rules.

Secondly, it does not matter what formulae are used for comparison purposes, as long as all configurations are analysed using the same (internally consistent) group of formulae. The ranking of the configurations will be the same for a particular factor.

The pass/fail limit will however differ, depending on the formula used. The factor which has the greatest impact in this respect has been found to be the factor of foundation design. A design using the SAIEE (1966) formula for foundation design (Equation 3.14) requires that the soil should have a bearing capacity nearly three times that required for a design using the Schepers & Good (1985) formula (Equation 3.20A). This anomaly is even more obvious when a safety factor of 2 is used. The required load-bearing property of the soil is obtained by multiplying the values calculated in Section 3.5 (as listed in Part 3.5.8) by the safety factor. The results are compared to given values for "average" soil as follows:

Origin	Calculated Value	"average"soil (as defined by the authors)
SAIEE (1966)	1 088 kPa	345 kPa
Schepers & Good (1985)	382 kPa	380 kPa

The calculations using the Schepers & Good (1985) formula give an acceptable answer (the pole will not overturn) whereas the SAIEE (1966) formula clearly implies that the pole will overturn under the specified conditions.

The above calculations were based on a 150m span of Mink conductor subjected to a wind load of 700Pa. Decreasing the span to 50m (without changing any other conditions and using a safety factor of 2) gives a calculated value (SAIEE, 1966) of 488kPa which is still in excess of the value of 345kPa for "average" soil. The implication of this fact is that lines designed using the SAIEE (1966) formula are under-designed. It would be expected, if the lines were in fact under-designed, that a large number of rural lines would fail in service by overturning. This is not so. General experience throughout the distribution Regions of Eskom is that there have been minimal failures of rural lines from any cause, least of all from overturning. Overturning, in any event, is considered to be a "preferred mode of failure" as service is not generally interrupted and the line can be restored with a minimum of effort.

The issue that now emerges from the above discussion is that the SAIEE (1966) formula for foundation design appears to be suspect. The calculated results do not confirm what is happening in practice as indicated by the minimal failure of lines by overturning. Despite this it was decided to retain the use of this foundation formula when doing comparisons. The reasons for doing this were twofold. The formulae used for the comparisons would all still have a common origin, namely the Code of Practice (SAIEE, 1966) and thus should at least be internally consistent regarding units and derivations. The formula would still give the correct ranking of the various configurations but the calculated values for limiting spans would have to be evaluated relative to practical experience. This latter aspect will be discussed in more detail at a later stage.

The longest span used in the calculations is in excess of 300m, although common construction span lengths are of the order of 100m to 150m. The limiting span has to be calculated for each configuration in order to fully explore its theoretical limitations.

The conductors that are used in the analysis are Fox, Mink and Hare as these are of the type (ACSR) and sizes most widely used in South African practice.

The pole used for the analysis is 11m pine pole (*Pinus Radiata*) with a 160mm top diameter and a taper of 5mm in diameter per metre of length. The pole is representative of common practice in South Africa (and overseas) in size and strength. Different pole sizes or materials will be considered during the analysis if their use will remove a limitation imposed by the above pine pole.

The eight Parts of this Section cover the factors used in the analysis. The results of the calculations for each comparison factor are presented in graphical or tabular form. The ranking of the configurations with respect to each factor is clearly shown. The pass/fail criteria are discussed in each Part, where applicable.

In the first Part the ground clearance is obtained for each configuration as a function of sag (and therefore of the span) and of conductor attachment height relative to the setting depth of the pole. Ground clearances are compared to the required statutory limits.

The second Part examines the stress developed in the pole at ground level due to wind load forces on the total pole structure and conductors for each configuration. The permissible pole stress is discussed relevant to its effect on the maximum span.

The same wind load forces are used in third Part and the bearing capacity of the soil to prevent overturning of the pole is calculated. The soil bearing capacity is used to determine the maximum span for each configuration.

Horizontal and vertical spacing of the conductors for each configuration is assessed in the fourth Part and the maximum permissible span obtained for each.

The fifth Part compares the effect the geometry of the configuration has on the volt drop along a line.

The hazard that such rural distribution line structures pose to bird-life is discussed in the sixth Part.

The seventh Part contains a detailed estimation of costs and makes cost comparisons over a range of variations of the standard configurations.

The costs of construction of rural lines are compared and discussed in the last Part.

4.3.1 SAGS AND CLEARANCES

This Part analyses the limitations of the configurations with respect to ground clearance. The sags of the conductors are calculated and referred to the different conductor attachment heights for each configuration. The statutory ground clearance (MOS Act, 1983) is the limiting value.

The equations necessary for calculating sags and spans are obtained from Chapter 3, Section 3.3.

The tension in the conductor must first be calculated in order to calculate the sag for each span. The basic design conditions of a temperature of -5°C (t_1), a wind pressure of 700Pa (MOS Act, 1983) and a conductor tension of 25% UTS (H_1) were used in the formula below for state 1.

The above data and that for the three conductors under consideration, Fox, Mink and Hare (Figure 3.07), was used to calculate the conductor tensions (H_2) at 50°C (t_2) for no wind (state 2) over the range of spans from 50 to 300 metres. (An example calculation of this kind was done in Part 3.3.3.)

The 50°C conductor temperature is the required minimum temperature for the calculation of sag (MOS Act, 1983). Should the conductor temperature be expected to exceed 50°C then the appropriate temperature would be used in the calculations. It is unlikely that this would be so for the majority of rural distribution lines.

The equation of change from state 1 to state 2 (Equation 3.3) is repeated below for the convenience of the reader:

$$l^2((w_1/H_1)^2 - (w_2/H_2)^2)/24 - e(t_1 - t_2) - (H_1 - H_2)/EA = 0$$

where:

l is the span (metres)

H_1 and H_2 are the horizontal tensions (N)

w_1 and w_2 are the resultant loads (N/m)

t_1 and t_2 are the temperatures (°C)

e is the coefficient of expansion (°C⁻¹)

E is Young's modulus (N/mm²) (final value)

A is the cross-section area of the conductor (mm²)

Note: The resultant loads are calculated from the unit conductor mass (vertically down) and the unit wind load (horizontal), both in N/m.

The calculated conductor tension was used in the catenary equation (below) to calculate the sag. The catenary equation is given by:

$$s = w_c l^2/8H + (w_d/6H)(w_c l/8H)^2 + 0,4(w_d/6H)^2(w_c l^2/8H)^3 \quad (\text{Equation 3.1})$$

where:

s is sag (m)

w_c is the unit mass of the conductor (N/m)

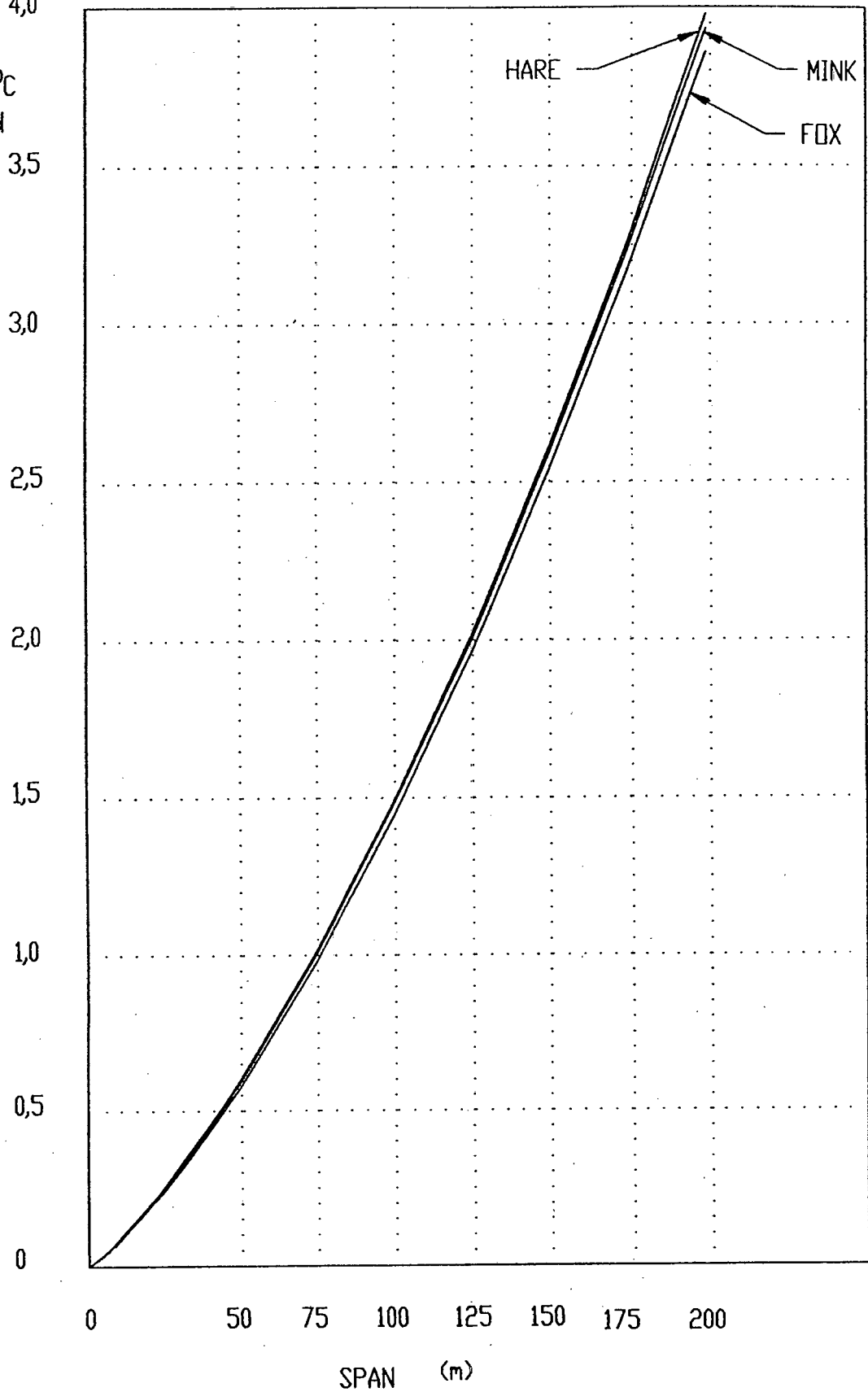
l is the span (m)

H is the horizontal tension (N)

Each of three conductors (Fox, Mink and Hare) has a six to one (aluminium to steel) stranding ratio. This means that the sags are virtually all the same when they are pulled up to their individually correct tensions (based on 25% UTS). This can be seen in Figure 4.09. The maximum difference in sag at a span of 200m is less than 3% (102mm in 3 918mm). The difference is due to rounding-off errors and variations in manufacturers' data. For this reason it was decided to use the "average sag" (that of Mink) in the clearance comparisons.

Once the sag for each span has been calculated then these figures have to be related back to the pole-top conductor configuration under consideration. It is only the position of the lowest conductor which needs to be considered, relative to the ground.

SAG 4,0
(m)
at 50°C
no wind



CURVES OF SAG vs SPAN FOR FOX, MINK AND HARE CONDUCTORS

FIGURE 4.09

The above-ground clearance is given by: $h + h_a - s$ (m)

where:

h is the pole length (m)

h_a is the attachment height above the pole top (m)

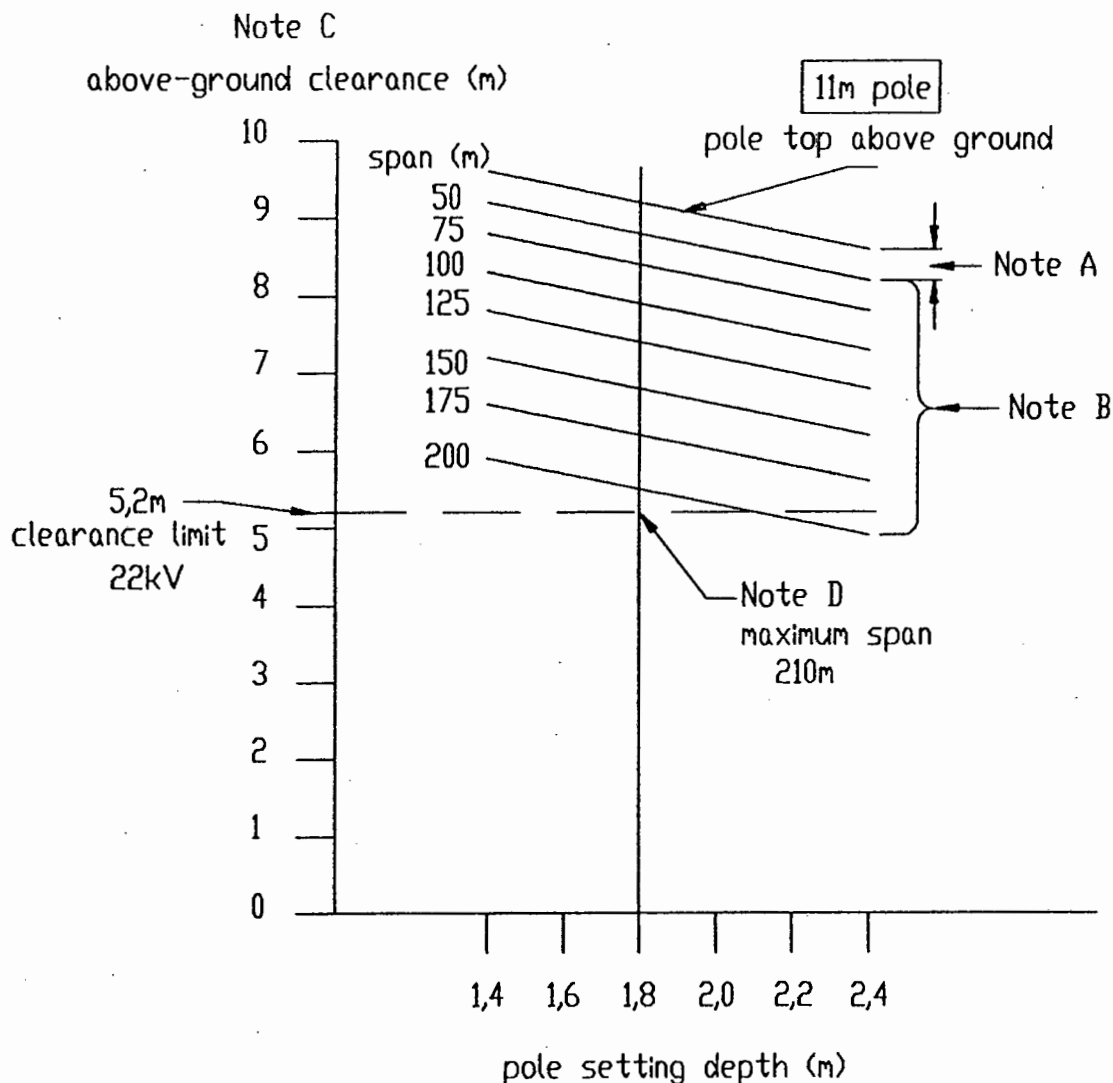
s is the sag (m)

Figure 4.10 is an example of a "Maximum Span vs Clearance" chart for the Horizontal configuration. This chart is completely general in form in that any other span/clearance chart can be derived from it by positioning the "sag/span lines" (Note B on Figure 4.10) at the appropriate attachment height for the lowest conductor. The chart will apply to any conductor with 6/1 equal diameter stranding.

Figure 4.11 summarises the data calculated for maximum spans and a ground-clearance limit of 5,2m (as specified in the MOS Act (1983)) for each of the pole-top configurations. It is drawn on the basis of different setting depths for an 11m pole. The various configurations determine the relative position of the lowest conductor with respect to the top of the pole and hence above ground level.

The graphs in Figure 4.11, when redrawn with respect to the conductor attachment height above ground (and not to the pole top), form part of a continuous curve. This curve is, in fact, the sag curve of Figure 4.09 with the axes interchanged and a constant (the allowed clearance of 5,2m for 22kV) added. Figure 4.12 shows the two maximum span curves for 11kV and 22kV. The 22kV and 11kV curves intercept the X-axis at the clearance limits of 5,2m and 5,1m respectively. Any other maximum span curve can be produced (for these specific conductors) by effectively moving the curve horizontally so that the X-axis intercept is at the required mid-span clearance.

The limitation on span length due to limited clearance is only one of a number of factors which should be considered. If this is the crucial factor for a particular application of a configuration design then a longer pole or even a different configuration could be used. The particular circumstances would then be taken into account for only that specific situation.



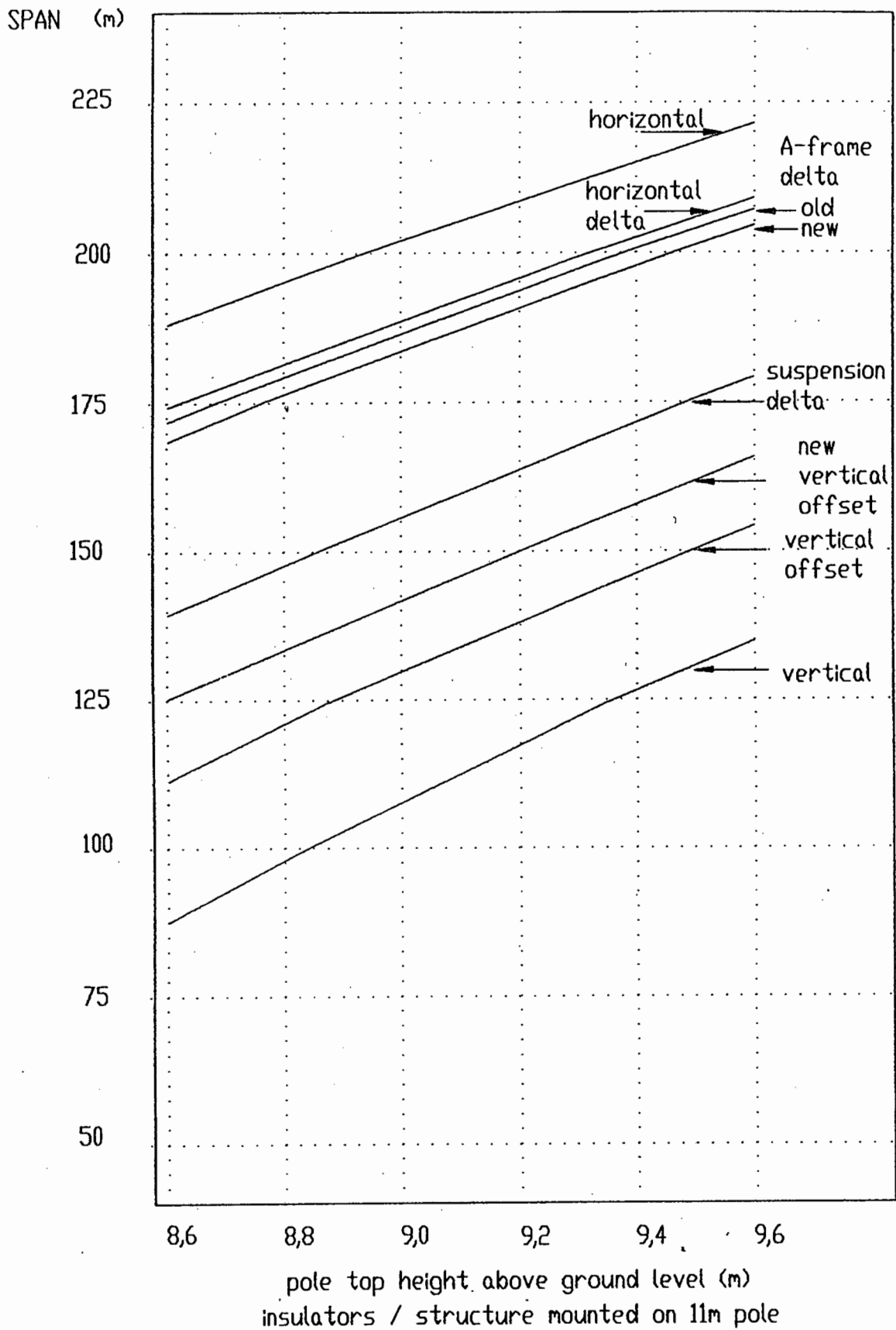
Note A: This distance is the sum of the attachment height below the pole top plus the sag for a 50m span.
(Attachment heights are given in Figure 4.01.)

Note B: The vertical spacing of these lines depends only on the sag of the conductor for the various spans. Their relative positions thus remain unchanged and they are moved vertically as a group depending on the attachment height of the lowest conductor.

Note C: Above-ground clearance is defined as:
pole length - setting depth + attachment height above pole top - sag

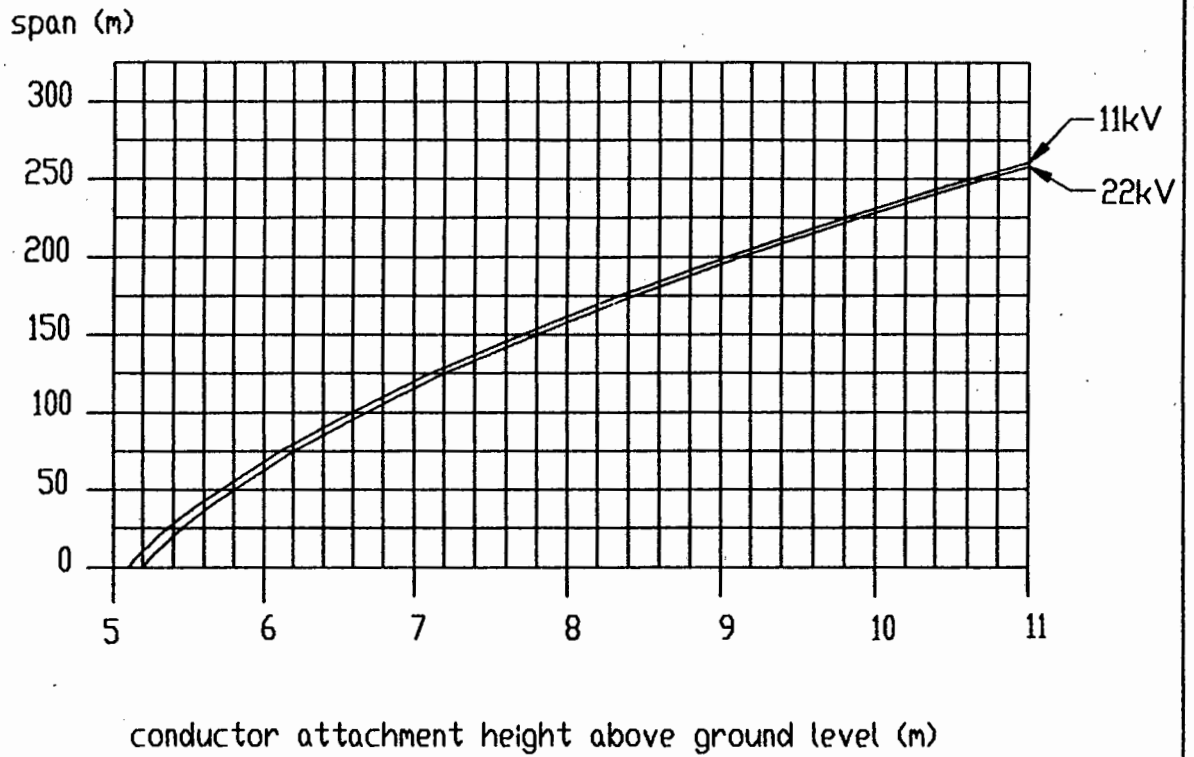
Note D: This is the maximum span possible for the specified clearance limit and for a 1,8m pole setting depth.

EXAMPLE CHART
MAXIMUM SPAN vs CLEARANCE CHART FOR THE HORIZONTAL CONFIGURATION



MAXIMUM SPANS FOR VARIOUS CONFIGURATIONS : CLEARANCE LIMIT OF 5,2m

FIGURE 4.11



MAXIMUM SPAN USING SAG @ 50°C (AVERAGE FOR FOX, MINK, HARE)
FOR REQUIRED GROUND CLEARANCE AT 11kV AND 22kV

FIGURE 4.12

4.3.2 STRESS DEVELOPED IN A POLE AT GROUND LEVEL

The stress in an intermediate pole is evaluated in this Part. The maximum span possible, in terms of this factor, is limited by the ability of the unstayed pole to withstand the bending stress. The stress developed in the pole at ground level for each of the eight configurations and for each of the three conductors over the range of spans is calculated and the result presented in graphical form.

The forces and the distances of their points of action from ground level are calculated by using the formulae obtained from Chapter 3, Section 3.4: (Note: These formulae and calculations are also used for the evaluation of the resistance of the soil to overturning of the pole.)

The formulae were used to calculate the stresses for each of the configurations. An example of the calculation is given in Part 3.4.4.

The results of the calculations for a minimum design wind pressure of 700Pa (MOS Act (1983)) are presented in Figure 4.13. (700Pa is equivalent to a wind speed of 123km/h at sea level) There are five graphs for each conductor type instead of the possible eight because, as can be seen from the notes on Figure 4.13, six of the configurations are grouped in three pairs.

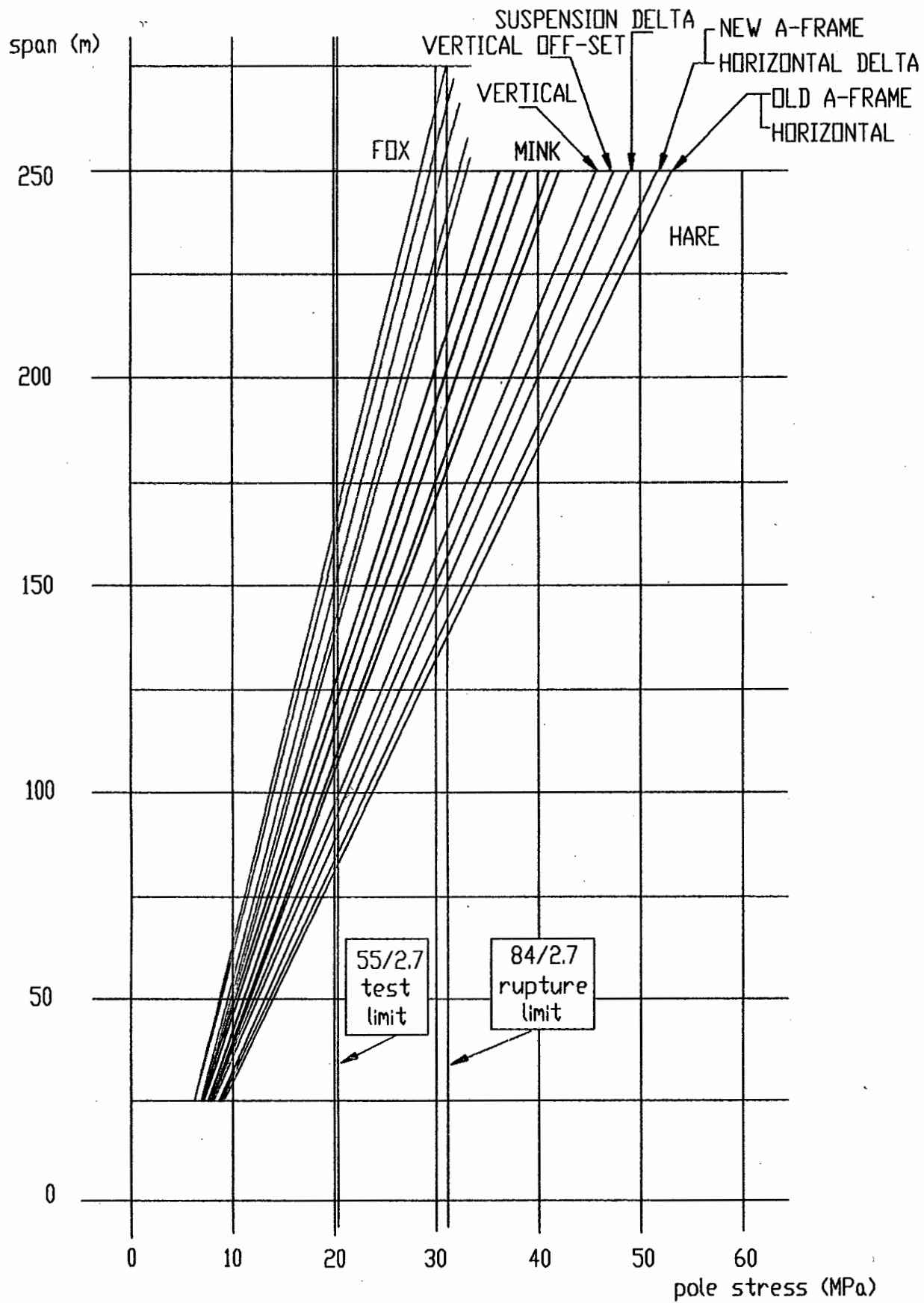
It was decided to present only the data for the case of an 11m pole with 1,8m setting depth as this is virtually a world-wide "industry standard" as mentioned in the introduction to the Chapter.

The vertical line for the rupture limit of 84MPa (using a safety factor of 2.7 (MOS Act, 1983)) shows that no structures would exceed this limit, below spans of about 135m. The test limit of 55MPa fibre stress has also been shown.

The "worst-case" configurations (those which result in the highest stress in the pole) are the OLD A-FRAME and the HORIZONTAL configurations. The A-FRAME has a larger crossarm area than any other and also carries the conductors high up the pole (as does the HORIZONTAL configuration).

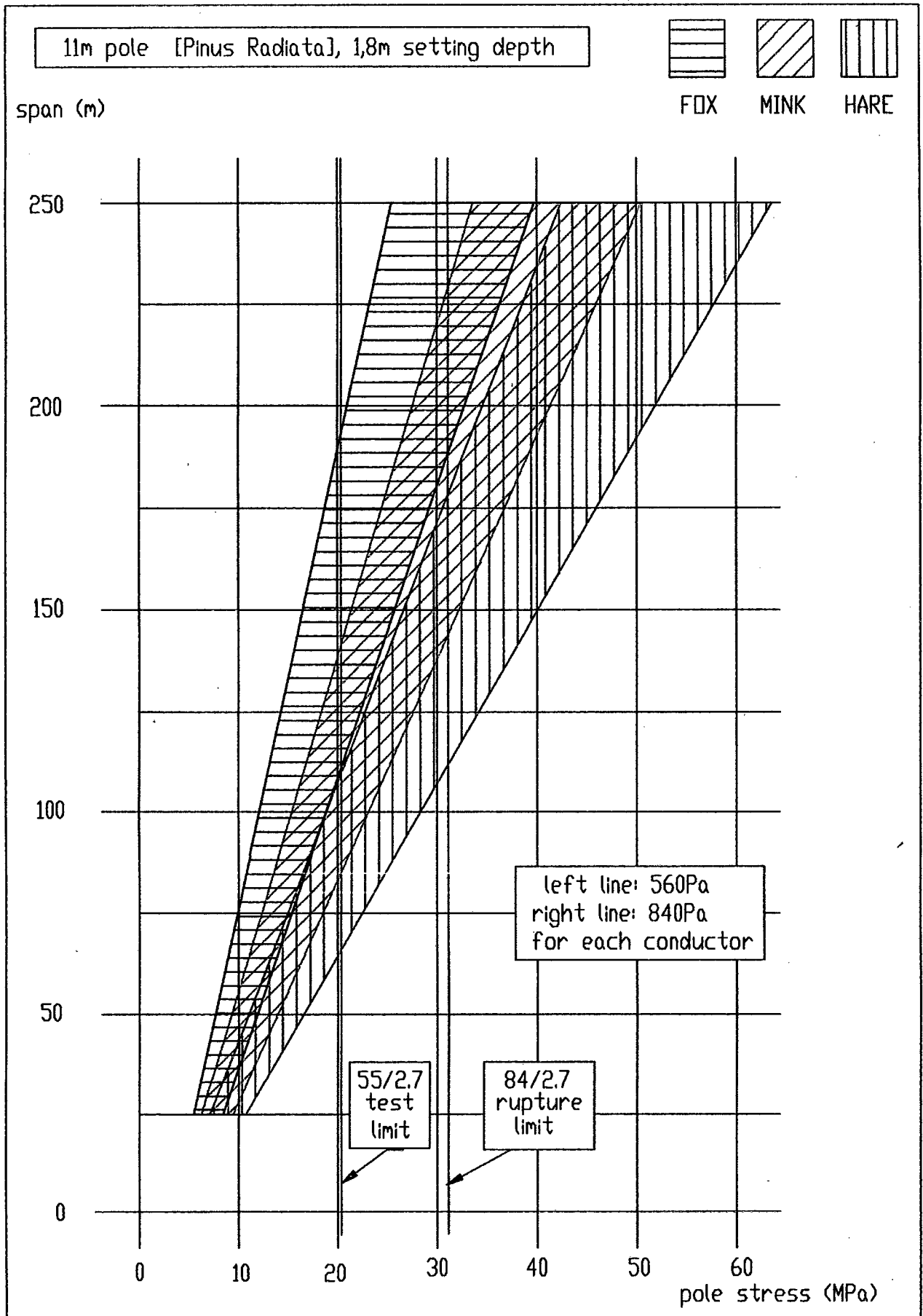
The data from these "worst case" configurations is used to calculate the information for Figure 4.14. The effect that different wind pressures may have on pole stress is shown in this figure.

11m pole (Pinus Radiata), 1,8m setting depth



STRESS DEVELOPED AT GROUND LEVEL IN POLE AT A WIND PRESSURE OF 700Pa FOR FOX, MINK and HARE CONDUCTORS FOR VARIOUS CONFIGURATIONS

FIGURE 4.13



STRESS DEVELOPED AT GROUND LEVEL IN POLE OVER A RANGE OF WIND SPEEDS FROM 560Pa TO 840Pa FOR FOX, MINK and HARE CONDUCTOR FOR THE 'WORST CASE' CONFIGURATION (OLD A-FRAME).

FIGURE 4.14

Each "area", for a specific conductor covers the range of -20% to +20% of 700Pa (560Pa to 840Pa) in wind pressure in order to illustrate the effect different wind pressures would have on the stress in the pole. (560Pa and 840Pa wind pressures are equivalent to a wind speeds of 110km/h and 135km/h respectively.) None of the configurations cause the 84MPa stress limit (safety factor 2,7) to be exceeded, even for this "worst case" situation.

None of the configurations will cause the pole to be overstressed on the basis of a 84MPa stress limit at a safety factor of 2,7 below a span of about 135m. It can be seen from the graphs in Figures 4.13 and 4.14 that the Hare conductor (having the largest diameter) will cause the biggest stress.

Practical experience of lines using spans of more than 100m with these pole structures is limited, as they have been in use for only the last five years. Pole failures, when they have occurred, have not generally been on intermediate structures. Failures have also not been caused by overstressing due to wind load on a sound pole but have been caused by external or internal damage (rotting or knotholes) (Eskom, 1991).

4.3.3 RESISTANCE OF THE SOIL TO OVERTURNING OF THE POLE

In this Part the moments that the different configurations exert on their foundations is examined. The overturning forces caused by the wind are the same forces that cause bending stress in the pole. The pole will tend to overturn when the actual soil resistance is too low to withstand the imposed moment. The same results for total imposed moment, as calculated for the previous section, are used here. In order to apply the results, the distance that the total force acts from the ground line is also required. The relevant equations from Chapter 3, Section 3.4 were used for the calculations.

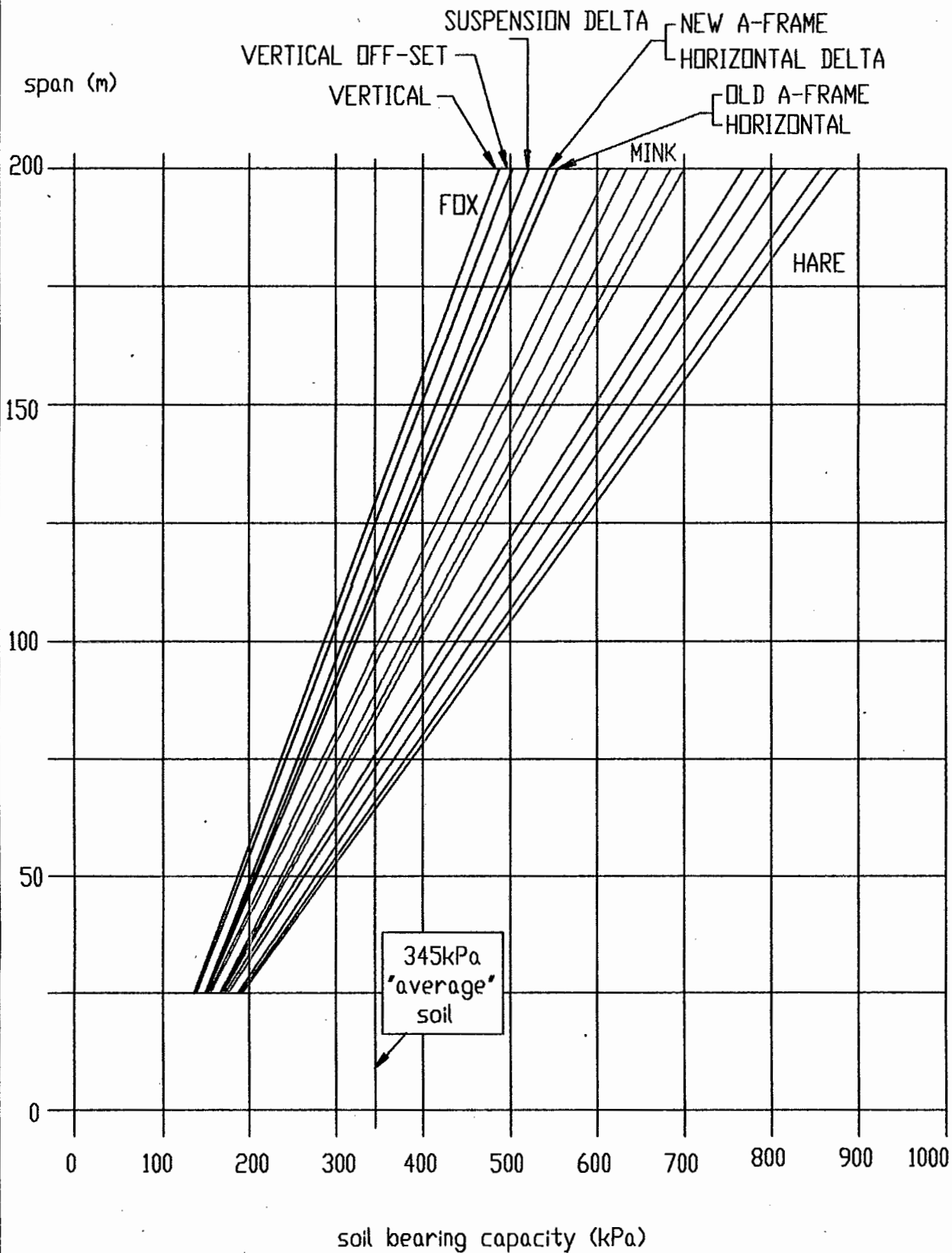
Equation 3.14 was used to calculate the soil bearing capacity required to prevent overturning of the pole. An example of the calculation is given in Part 3.5.2. No safety factors were taken into account in the equation. It was considered that a safety factor would obscure the actual limitations of the structures for the reasons given in the introduction. The calculations were done for each of the eight design configurations and for each of the three conductors over the range of spans.

The results of the calculations for a minimum design wind pressure of 700Pa (MOS Act (1983)) are presented in Figure 4.15. There are five graphs for each conductor type instead of the possible eight because, as can be seen from the notes on Figure 4.15, six of the configurations are grouped in three pairs. The graphical presentation thus looks similar to that for the calculations on pole stress.

The results for overturning are similar to those for pole stress. The "worst-case" configurations are the same, as is expected, and for the same reasons. They are the OLD A-FRAME and HORIZONTAL configurations. The data from these "worst case" configurations is used to calculate the information for Figure 4.16. The effect that different wind pressures may have on the required soil bearing capacity is shown in this figure.

Soil conditions are not accurately known and also vary over a wide range of values not only geographically, but seasonally. A line built in a dry season may well tend to overturn in the wet season. It has been assumed that typical values for soil bearing capacity in areas where rural distribution lines at 11kV and 22kV may be built lie in the range of 200kPa to 500kPa. (See Figure 3.03 in Chapter 3.) There may be some doubt about the upper limit, as will be seen

11m pole [Pinus Radiata], 1,8m setting depth, average hole diameter 210mm



REQUIRED SOIL BEARING CAPACITY TO PREVENT OVERTURNING FOR FOX, MINK and HARE CONDUCTORS AT A WIND PRESSURE OF 700Pa FOR VARIOUS CONFIGURATIONS

FIGURE 4.15

11m pole [Pinus Radiata], 1,8m setting depth
average hole diameter 210mm



FOX

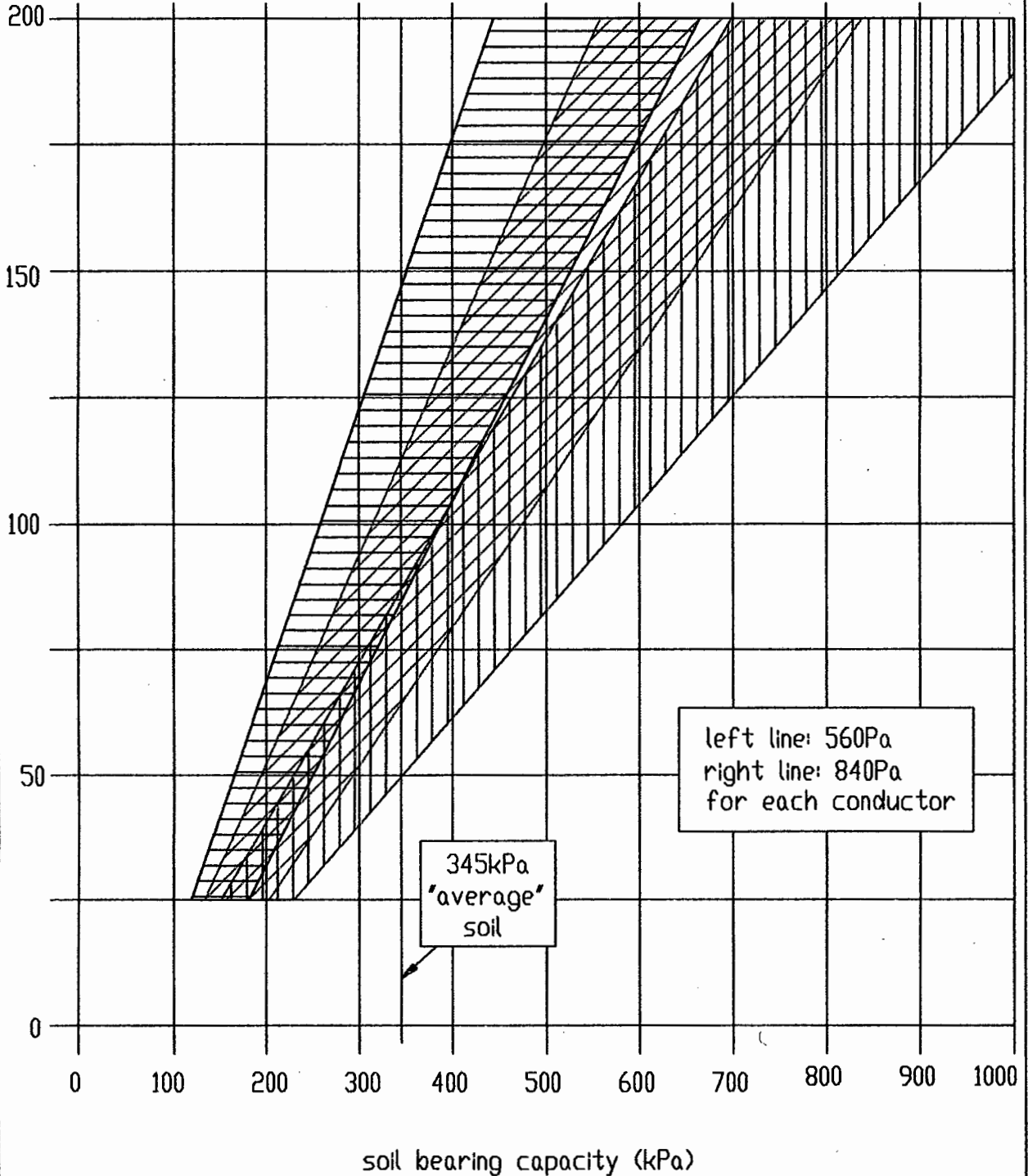


MINK



HARE

span (m)



REQUIRED SOIL BEARING CAPACITY TO PREVENT OVERTURNING
OVER A RANGE OF WIND SPEEDS FROM 560Pa TO 840Pa FOR FOX, MINK and HARE
CONDUCTOR FOR THE "WORST CASE" CONFIGURATION (OLD A-FRAME).

FIGURE 4.16

from the discussion below. Whatever the soil conditions are found to be along the actual line being built will determine what limitation there is on the maximum span that can be used.

The maximum span for any configuration using Hare conductor is a "best case" of 120m and a "worst case" of 105m for a soil bearing capacity of 500kPa and a wind pressure of 700Pa (Figure 4.15). This is not as good as it may seem as no safety factors have been taken into account in the calculations.

A safety factor of 2 (SAIEE, 1966) would halve the soil bearing capacity and span lengths would drop to less than 100m. The figure of 345kPa is used by the Code (SAIEE, 1966) for "average" soil, and a safety factor of 2 applied to this figure would mean a design bearing capacity of about 173kPa. This is clearly not correct as no structures could (theoretically) be built with spans longer than 40m in "average" soil. It appears to be obvious that either the value for the soil bearing capacity is wrong or the design or formula is wrong. The range of values given for maximum safe bearing capacity for various soils given in Figure 3.03 indicates that 345kPa is a good average value. It may even be considered to be on the high side. The indication is thus that the value for this property of the soil is correct and that indeed the SAIEE (1966) formula is wrong if a safety factor is used. The fact is that many kilometres of rural lines are built and very few lines fail.

The mechanism of failure (in this case) is not a "fracture" failure, which is rapid. Foundation failure occurs gradually; as the limiting bearing capacity of the foundation is approached, the soil tends to give way. As a result, the pole leans over and the more the pole leans, the less the wind-induced overturning moment becomes. It must also be remembered that in the practical situation the pole (here assumed to be rigid) bends, thus also relieving the pressure on the soil. The wind pressure on the structure is also not continuous at 700Pa, but comes in gusts.

The limit used for the comparison of the structures has been taken as 345kPa (from the Code of Practice (SAIEE, 1966)) without the use of a safety factor. This has been done on the basis of the logic outlined above. The safe design bearing capacity (without a safety factor) is inferred from the fact that there are very few failures of rural lines. The question of foundation design needs more in depth investigation as there are too many uncertainties.

4.3.4 CONDUCTOR SPACING AND SPAN LIMITATIONS

This Part of the Section on the analysis of South African practice deals with the limitation that conductor spacing has on the theoretical maximum span for a particular configuration. The horizontal conductor spacing for each configuration is plotted on a graph of span versus spacing for 11kV and 22kV. Vertical spacing is not seen as a limiting factor. The Code of Practice (SAIEE, 1966) states that vertical separation could be as close as the minimum phase-to-phase clearance required. The VERTICAL configuration is the only configuration where vertical spacing is relevant. In this case the spacing is more than 0,6m greater than the required minimum.

The SAIEE equation for conductor spacing is given as (Chapter 3, Part 3.6.2):

$$c = l/200 + c_p \quad \text{m} \quad \text{(Equation 3.24)}$$

where:

l is the span length (m)

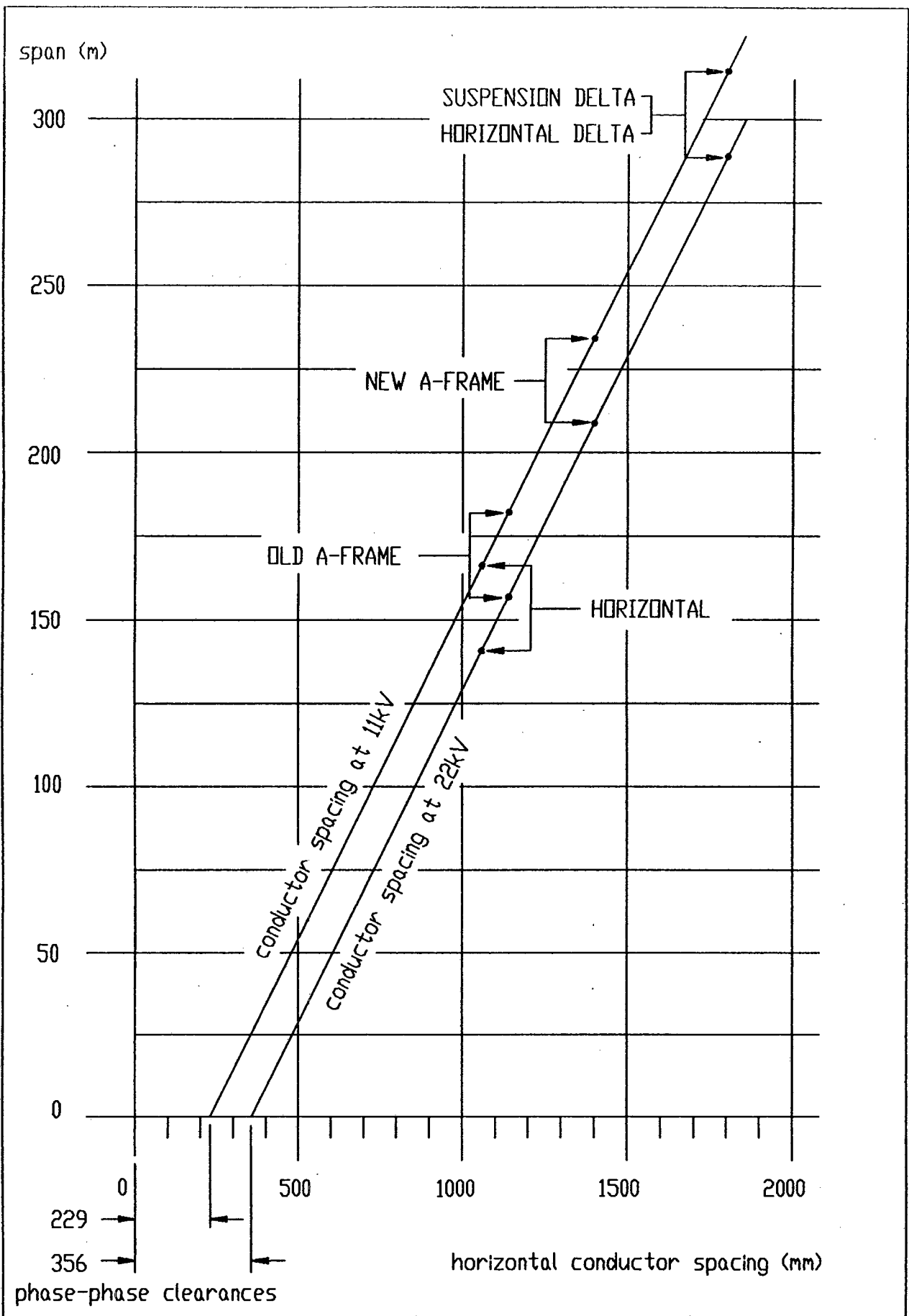
c_p is the phase-to-phase clearance (m)

(0,229m for 11kV; 0,356m for 22kV)

The above equation was used to calculate the range of horizontal spacing applicable at 11kV and 22kV to the range of spans. This data was used to plot the two lines on Figure 4.17 which represent the maximum permissible span for a particular horizontal spacing of the conductors.

Each of the configurations which have conductors attached in a horizontal plane, has been plotted on the graph. Those configurations which have no conductors attached in a horizontal plane are not shown on the plot as they have a theoretically unlimited span capability, in this instance, as far as this factor is concerned.

The limitation on the span length because of the horizontal spacing of the conductors is only a rigid limitation for a particular configuration. The maximum theoretical span limit can be changed for this factor by various means, the simplest of which is by lengthening the crossarm. As another example, the maximum allowable span can be doubled by raising the centre conductor in a HORIZONTAL configuration by only a relatively small amount (say, 300mm); effectively making it a HORIZONTAL DELTA configuration. The introduction of the NEW



MAXIMUM SPANS WITH REFERENCE TO CONDUCTOR SPACING AT 11kV AND 22kV FOR VARIOUS CONFIGURATIONS

FIGURE 4.17

A-FRAME configuration was aimed specifically at increasing the span by increasing the horizontal conductor spacing. (The SAIEE (1966) formula was used for the calculations.)

It is particularly difficult to prove the theory of conductor spacing in practice. The "failure mode" in this instance is that the conductors approach within arcing distance under the appropriate wind conditions. The resulting short circuit phase-to-phase fault is cleared by the line protection and the only indication that there had been a fault is that the protection had operated. The cause of the fault (conductors coming too close to one another or actually clashing) is transitory. There may be hard evidence such as signs of arcing on a conductor, but it is very difficult in practice to find such proof, considering the length of line that would have to be carefully examined. The only "proof" that arcing or contact had probably taken place would be if all other possible causes (birds, animals or other objects across the phases) had been eliminated. The indication that this mode of failure had occurred could be inferred from the number of phase-to-phase faults detected without apparent cause.

Horizontal spacing is not a rigid limitation in practice. The (theoretical) maximum span can be easily increased by using a different (standard) configuration with a larger horizontal phase separation or by using a non-standard configuration for the instances where this factor of horizontal spacing may be a limitation.

4.3.5 VOLT DROP ALONG A LINE

There are not many electrical factors that can be used to compare pole-top configurations with one another. The volt drop and line losses are proportional to the resistance of the line, which is a function of only the conductor and the length of the line. The volt drop along the line is however also a function of the inductance and of the capacitance of the line. These in turn are functions of the configuration and/or spacing of the conductors.

The volt drop along a rural distribution line is evaluated in this Part. The calculations have been done for each of the eight configurations and three conductors being analysed. The analysis is based on the theory discussed in Chapter 3. The inductance and capacitance formulae are derived from relations for a fully-transposed line. This transposition is done when the three conductors are unequally spaced relative to one another in order to balance the inductance and capacitance effects. The positions of the conductors on the structure are changed twice in the length of the line so that each phase occupies a different position for one third of the line. Transposition is usually done for only long transmission lines (132kV and above) and the development of the theory (Freeman, 1974) is based on such lines. It is assumed that the theory applies equally well to rural (11kV and 22kV) lines and can be used to evaluate whether actual (calculable) differences exist between the different configurations.

The equations for the calculation of inductance, capacitance and volt drop are given in Chapter 3, Part 3.8.3.

The average inductance per phase is given by:

$$\text{inductance} = L_1 + 0,2 \ln(c_d/r) \quad \text{mH/km} \quad (\text{Equation 3.31})$$

The average capacitance per phase is given by:

$$\text{capacitance} = (18 \ln(c_d/r))^{-1} \quad \text{microfarad/km} \quad (\text{Equation 3.32})$$

A formula for the calculation of voltage drop for a long line is:

$$\text{volt drop (phase voltage)} = (R/2 + jX_L/2)(2I_R + \{j[V_R + I_R(R/2 + jX_L/2)]\}/X_C)$$

(Equation 3.33)

The above equations were used to calculate the inductance and capacitance per phase of a 10km rural distribution line. (10km was chosen as being representative of an "average" line length.) The receiving end line voltage was taken as 22kV and the magnitude of the sending end line voltage line was calculated at the rated current of each conductor for a load power factor of 0,9.

The detailed data used in the calculations is shown in Table 4.01. There is very little difference (less than 0,3%) between the sending end voltages for any configuration.

The volt drop is a proportional function of line length and current. The sending end voltages required for a receiving end voltage of 22kV are plotted in Figure 4.18 as a function of a "separation function". This "separation function" is the ratio between the effective spacing of the conductors (c_e) and the conductor radius (r).

The small differences between the volt drop performances of the various configurations, as typified by the required sending end voltages, depend on the differences in effective spacing of the conductors. From the relation given for c_e above it can be seen that any geometric arrangement of three conductors can be made identical to any other in this one respect by simply making the values for c_e identical. Clearly, a change in geometry may influence other factors, but if warranted, changes could be made so that the effect on other factors is minimised. Changing the geometry while keeping the centre of gravity of the configuration fixed would not affect either the pole stress or foundation limitations. The span limitation due to conductor spacing would be affected, however (but may not be relevant as foundation strength may be the overriding limitation).

The analysis of this electrical aspect therefore does not yield results which should have a major influence on the selection of a particular configuration.

CONFIGURATION	C_e	$\ln(C_e/r)$			inductance (L) mH/km			capacitance (C) μ F/km			required V_s for a V_r of 22kV		
	(m)	FOX	MINK	HARE	FOX	MINK	HARE	FOX	MINK	HARE	FOX	MINK	HARE
Horizontal	1,34	5,76	5,49	5,24	1,47	1,43	1,39	0,0096	0,0101	0,0106	24,98	24,74	24,64
Vertical Offset	1,15	5,61	5,34	5,09	1,44	1,40	1,36	0,0099	0,0104	0,0109	24,97	24,72	24,62
New Vertical Offset	0,97	5,45	5,18	4,92	1,40	1,37	1,32	0,0102	0,0107	0,0113	24,95	24,70	24,58
Vertical	1,26	5,70	5,43	5,18	1,45	1,42	1,38	0,0097	0,0102	0,0107	24,97	24,73	24,63
A-Frame Delta	1,15	5,61	5,34	5,08	1,43	1,39	1,36	0,0099	0,0104	0,0109	24,97	24,72	24,61
Horizontal Delta	1,18	5,64	5,37	5,12	1,44	1,40	1,36	0,0098	0,0103	0,0109	24,97	24,72	24,62
Suspension Delta	1,37	5,79	5,52	5,27	1,47	1,43	1,39	0,0096	0,0101	0,0105	24,98	24,74	24,65
New A-Frame Delta	1,06	5,53	5,26	5,01	1,42	1,38	1,34	0,0100	0,0106	0,0111	24,96	24,71	24,61

	FOX	MINK	HARE
Resistance (R) ohms/km	0,782	0,455	0,273
Rated Current @ 75°C	190	260	360

V_s : sending end voltage
 V_r : receiving end voltage

DATA USED IN THE CALCULATIONS FOR THE REQUIRED SENDING END VOLTAGE FOR 10km OF 22kV LINE

TABLE 4.01

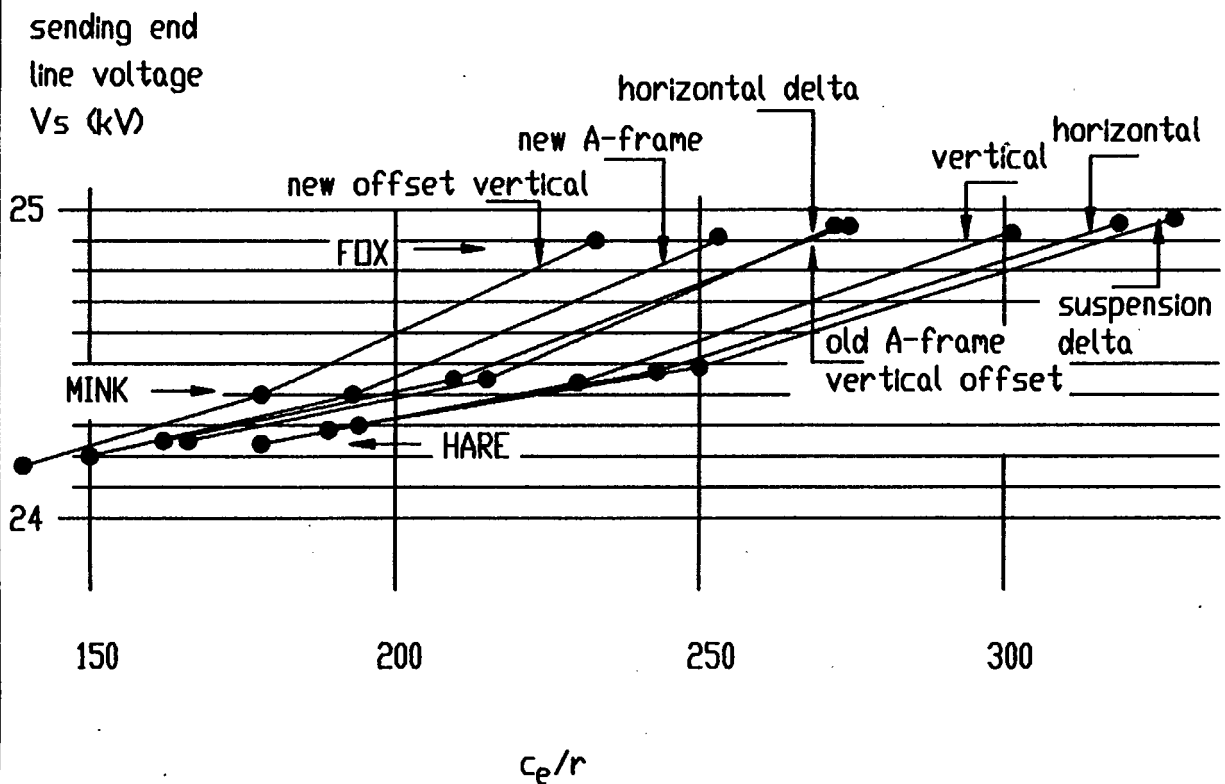
Separation Function = c_e/r

$$L = L_1 + 0,2 \ln (c_e/r)$$

$$c_e = \sqrt[3]{c_1 + c_2 + c_3}$$

$$C = (18 \ln (c_e/r))^{-1}$$

r = radius of conductor



GRAPHS OF SENDING END VOLTAGE versus SEPARATION FUNCTION FOR FOX, MINK AND HARE CONDUCTOR FOR A 10km 22kV LINE

4.3.6 ENVIRONMENTAL HAZARD

The effect that the various configurations may have on bird-life in particular is discussed in this Part.

There is no doubt that the many kilometres of rural lines that run across South Africa constitute a hazard to wildlife. It is also true that not every structure or span has actually taken the life of an animal or bird. The hazard tends to be concentrated in the habitats or on the flight-paths of birds.

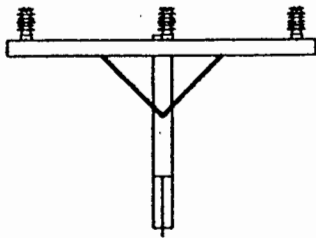
Large tracts of rural South Africa are virtually treeless. Any tall structure, such as an 11m pole planted in the ground with a convenient perch at the top, is bound to be an eyrie of prominence, even where there are trees.

Birds are killed by impact (with the conductors) or by electrocution (between phases or between a phase and earth).

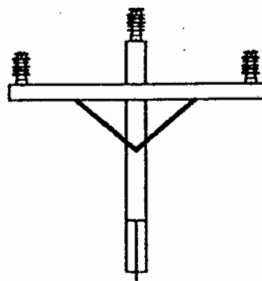
Figure 4.19 compares the eight selected pole-top configurations with the size of a Cape Vulture (Roberts, 1978). This comparison underlines the same-size relationship between the bird and the phase-to-phase or phase-to-earth spacing. It also serves to illustrate the "catch-net" effect that the conductors between the structures may have .

Fairly clearly the crossarms of the HORIZONTAL and HORIZONTAL DELTA configurations offer the probability of lethal perches to birds large enough to span the between-conductor gap. The SUSPENSION DELTA is a bird-friendly modification to the HORIZONTAL DELTA; the outer phase are "shielded" by the crossarm. However, if this structure were to have all the spindles bonded and earthed then it would be even more hazardous than if they were not electrically interconnected. Bare wires along the crossarm and pole would increase the risk of the bird bridging the gap between earth and a phase.

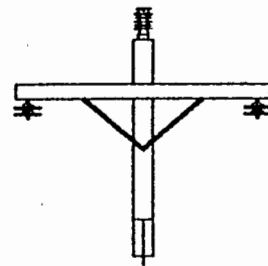
The two A-FRAME configurations both have the same advantage because of the sloping sides of the "A"; there is not enough space for a bird of any size to perch. Fault records for lines which use the OLD A-FRAME do not show major loss of wild-life which can be blamed on this



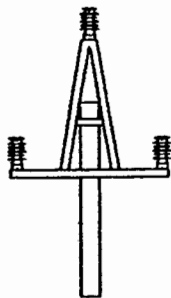
HORIZONTAL



HORIZONTAL DELTA



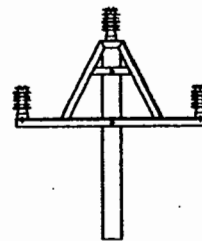
SUSPENSION DELTA



OLD A-FRAME



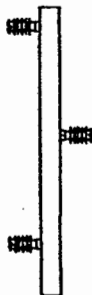
CAPE VULTURE



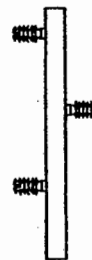
NEW A-FRAME



VERTICAL



OLD VERTICAL OFFSET



NEW VERTICAL OFFSET

THE EIGHT CONDUCTOR CONFIGURATIONS : THE CAPE VULTURE IS DRAWN TO SCALE

FIGURE 4.19

structure or configuration. The NEW A-FRAME was adapted from the old in order to provide a longer span and overall lower height.

There are no apparent hazards to perching birds from the three VERTICAL or VERTICAL OFF-SET configurations. Flight-path hazards or impact fatalities due to the birds flying into the conductors between the spans may tend to be higher for these configurations because of the close vertical position or vertical plane of the conductors.

The use of concrete poles in future will mean that the total structure will be fully bonded and earthed, because of the reinforcing in the concrete. This may put a new dimension on what constitutes a "safe structure" for perching birds in that even small birds could bridge the gap from earth (the top of the concrete pole) to the phase conductor.

It is a direct result of considerations such as the above that the HORIZONTAL and HORIZONTAL DELTA configurations using a horizontal wooden crossarm have been discontinued as it is considered by Eskom that they constitute an unacceptable risk to bird-life.

It is not possible or economic to replace all existing high-risk structures. The operating performance of a rural line has to be monitored to determine which of the existing high-risk structures are causing fatalities. These structures would then have to be modified or replaced with bird-friendly structures.

4.3.7 COMPARATIVE ESTIMATED COSTS FOR THE CONSTRUCTION OF RURAL LINES

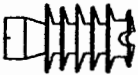
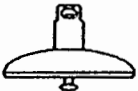



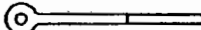


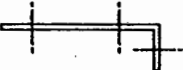



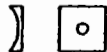

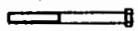


This Part of the Section on the analysis of South African practice is based mainly on the results presented in the first four Parts of the Section. These results, the maximum spans for which a configuration can be used, are functions of clearance, pole strength, overturning and horizontal conductor spacing and have a direct bearing on the cost per kilometre of the line.

The overall cost per kilometre of a rural line can be divided into three parts: the cost of materials, the cost of labour and the cost of the transport. The backgrounds and origins of these three groups of costs are discussed below.



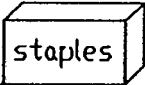
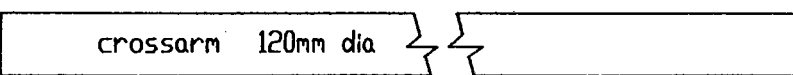
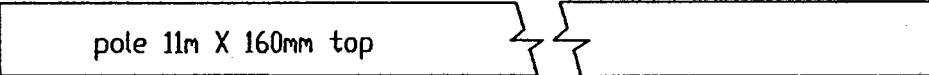
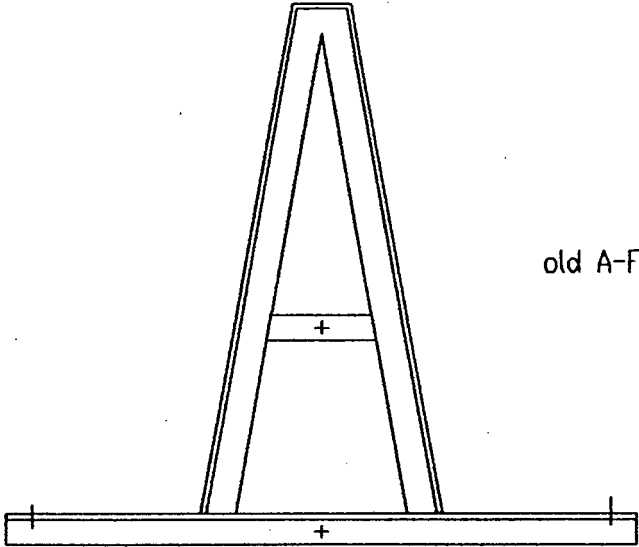
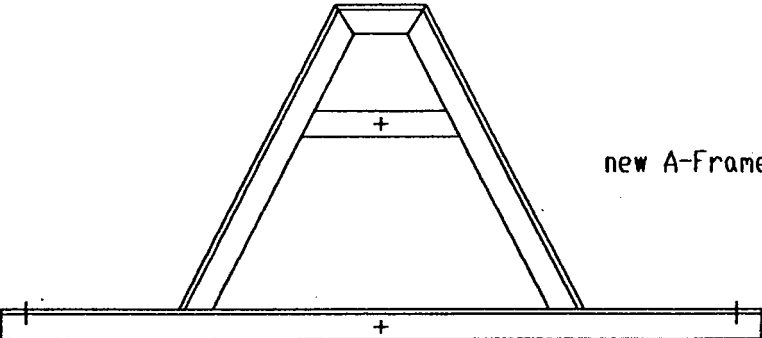
The cost of the materials per kilometre on a rural line consists of two components: the cost of the conductor and the cost per structure. The cost of the conductor depends on the type and size of the conductor. The lowest number of structures theoretically possible (for lowest cost per kilometre) depends on the maximum span possible for the particular configuration. The cost per structure is the total cost of the items making up the complete structure. Figures 4.02 to 4.08 give exploded views of each of the eight configuration structures considered in this Section. Figures 4.20 and 4.21 detail the costs of all the items used in the structures.

The labour cost is the cost associated with the workforce building the line. The workforce includes drivers, machinery operators, linesmen, erectors, labourers and construction foremen and supervisors. In addition there is the cost of housing and feeding the workforce when on site (the cost of the construction camp, its erection, staffing and operation).

The transport portion of the cost per kilometre of a rural line includes: transport of labour and materials to the base camp and the transport of labour and materials during construction. Also included is the cost of vehicles and vehicle-mounted equipment being used to build the line such as a vehicle fitted with a hydraulic crane, a pole borer or loaded with drums of conductor. The distances over which stores items are transported to the camp base are generally over 300km at present (there is very little expansion of rural schemes close to major centres). Transport of workers and materials from the base camp to the construction site could cover tens of kilometres over difficult terrain each day.

ITEM	DESCRIPTION	ITEM COST ¹⁹⁹¹ (cents)
	post insulator	4660
	disk insulator	4500
	clevis-ball adaptor	530
	socket-tongue adaptor	910
	cable clamp	2830
	eyebolt	530
	190mm spindle	680
	50mm spindle	450
	pole-top bracket	450
	spring washer 20mm	10
	flat washer 20mm	10
	curved washer	50
	concave washer	1500
	nut 20mm	40
	bolt 20mm x 230mm	360
	threaded rod 20mm x 230mm	520
	flat steel brace	490

ITEMS AND COSTS
FIGURE 4.20

ITEM and DESCRIPTION	ITEM COST 1991 (cents)
 <p>earth wire</p>	1000
 <p>wire Ⓞ washers Ⓜ clips</p> <p>] bonding and earthing components</p>	600
 <p>staples</p>	430
 <p>crossarm 120mm dia</p> <p>X 2000mm</p> <p>X 2400mm</p>	2900
 <p>pole 11m X 160mm top</p>	3500
 <p>old A-Frame crossarm</p>	17000
 <p>new A-Frame crossarm</p>	6700

ITEMS AND COSTS
FIGURE 4.21

PROCEDURE FOLLOWED IN CARRYING OUT THE COST ANALYSIS AND EVALUATION

The procedure adopted is outlined below:

The materials cost and labour content of each complete structure, not including transport, is first estimated. This is the estimate for assembling the complete structure, prior to the pole being set in the ground. Component and earthing variations for each configuration are included in this analysis, the results of which are shown later in Table 4.02.

This basic "per structure" estimate is then used with the number of structures per kilometre (for each configuration) and the cost of each size of conductor to obtain the estimated average cost per kilometre for each standard version of a configuration. The cost comparisons are based on known data obtained for the OLD A-FRAME configuration (Eskom, 1991). A complete summary of results giving these per kilometre costs is shown later in Table 4.03.

CLASSIFICATION OF COMPONENTS USED IN A POLETOP STRUCTURE

Classifications of the components, which are each accompanied by a brief discussion, are given below:

The components of each configuration design can be classified into five groups.

1. Insulators and spindles: Good practice requires a spring washer and one nut on a steel crossarm or bracket or a flat washer and two nuts on a wooden crossarm.

2. Crossarm assembly (if any) and means of fixing to pole: Threaded rods and two sets of flat washers and double nuts are used for wooden crossarms. Bolts, spring washers and single nuts are used for steel crossarms or brackets. Curved washers should be used wherever a nut (with washer) is tightened directly onto wood.

Threaded rods are used because the wooden poles used do not have a standard diameter or taper. This enables one stores item to be used in place of bolts of (say) three standard lengths. The labour content of fitting four nuts instead of one is obviously greater.

3. Pole: The pole is supplied with the required number of holes already drilled through it.

4. Components for bonding or earthing: Some of the "standard" designs are built to 300kV BIL. These, and the other designs, can be modified, at a small extra cost in components, to bonded (all spindles bonded) and/or fully earthed constructions. The labour cost involved is however comparatively high.

5. High-cost, "optional" components: These items are primarily the concave washers, which are included so that the two cylindrical components of pole and crossarm fit tightly together. (see exploded views; Figures 4.02 to 4.08) There is considerable argument about their usefulness and whether, in fact, they are even necessary. Similar arguments are used about the curved washers, although they are only a fraction of the price of a concave washer (50 cents versus R15).

A DESCRIPTION OF THE MEANS OF COMPARISON USED FOR THE LABOUR CONTENT

Devising a system for comparison of the assembly-labour content is not straightforward because the ideal of work-measurement data is not available. A means of fair comparison is required which can to a large extent reflect the time (or cost) for an operation or series of operations. It is possible to use rough estimates, as long as they are consistent.

The most common operation (and almost the only operation) in assembling a structure is to push a bolt through a hole, fit one or more washers or some other object (such as crossarm or brace) and fit and tighten a nut. Making up a sub-assembly (such as an insulator plus spindle) is a similar operation: fit one item into another item and tighten or clamp.

The assembly of each structure has therefore been analysed into "operations" of this kind, thus enabling simple comparisons to be made regarding the total time for assembly.

COST AND LABOUR ANALYSIS FOR EACH CONFIGURATION

The individual costs of all the items are shown in Figures 4.20 and 4.21. The costs for each standard configuration are based on the detailed designs as shown in Figures 4.02 to 4.08. The costs, item count and labour content are detailed in Table 4.02 for all variations of a configuration from basic to fully-bonded-and-earthed. The variations used are listed across the top of the Table. The basic data of material cost and labour content for assembling a standard poletop structure is used further on to calculate the per kilometre cost of rural line.

Figure 4.22 presents the data of Table 4.02 in a graphical form. The variation in cost from a basic to a complex structure is shown by the length of the lower bar for each configuration. The variation in the time taken (labour content) to build the structure is shown as the upper bar. Cost and labour for the standard design configurations are arrowed.

The A-FRAMES (new & old) have the lowest labour content, primarily because of the crossarm frame, which provides faster assembly and (unavoidable) bonding of the spindles.

The SUSPENSION DELTA is the most expensive, primarily because of the use of disk-type insulators. The overall cost per structure can be reduced by about R100 by the use of

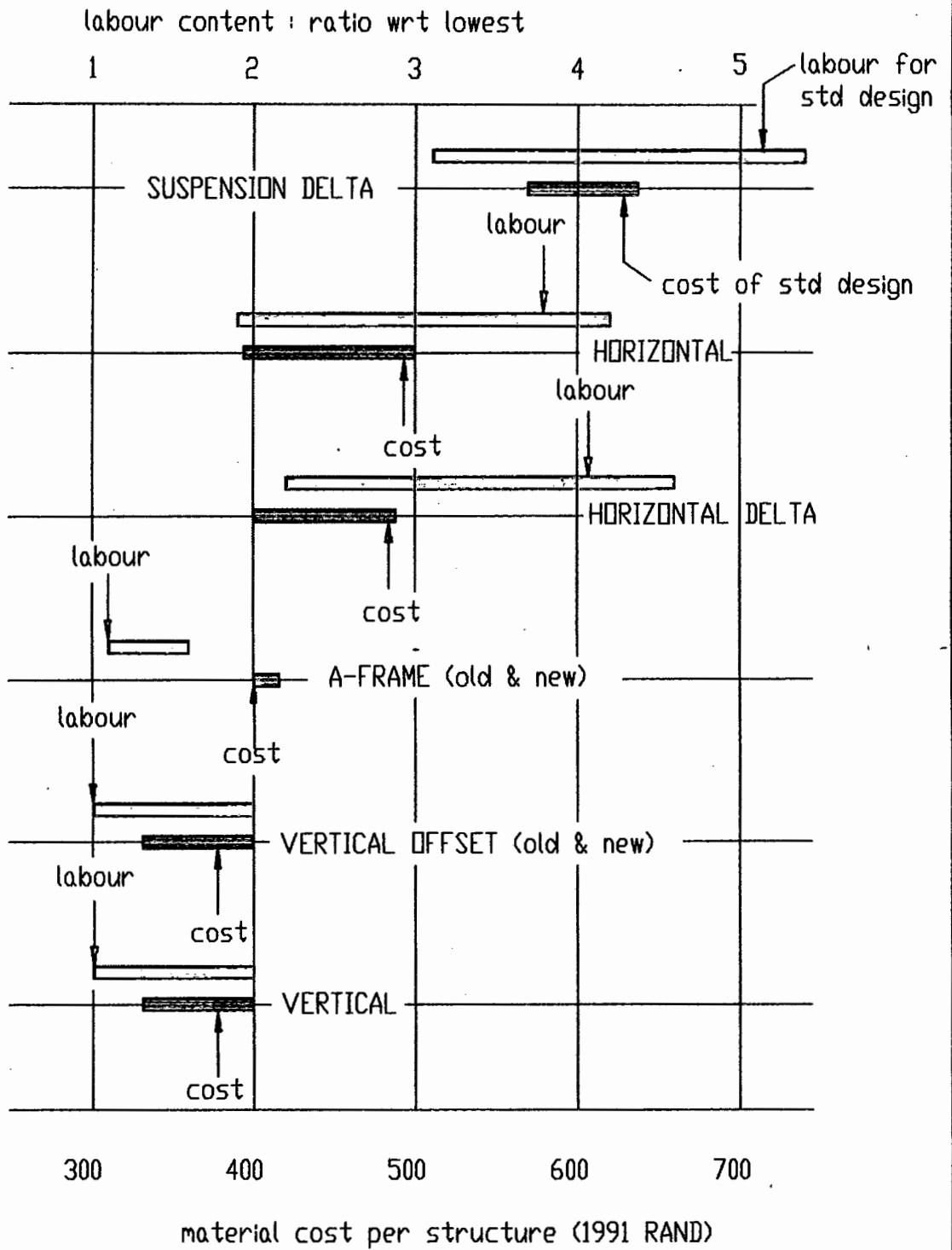
CONFIGURATION	STRUCTURE COMPLEXITY										
	← less					more →					
	BASIC STRUCTURE		plus CURVED WASHERS	plus CONCAVE WASHERS	SPINDLES unbonded		SPINDLES bonded				
bolts only	rods & bolts			2MV	300kV	2MV	300kV	300kV	earthed	BIL	
VERTICAL	10	10	13	16	16 *	18	17	19	20		
VERTICAL OFFSET (old & new)	10	10	13	16	16 *	18	17	19	20		
A-FRAME (old & new)	16	16	16	X	X	X	16 *	18	19		
HORIZONTAL DELTA	37	49	51	55	57 *	58	56	58	59		
HORIZONTAL	29	41	44	49	51 *	52	50	52	53		
SUSPENSION DELTA	49	61	65	67	69 *	70	68	70	71		
VERTICAL	331	331	333	378	378 *	392	384	398	400		
VERTICAL OFFSET (old & new)	331	331	333	378	378 *	392	384	398	400		
A-FRAME (old & new)	399	399	400	X	X	X	400 *	414	416		
HORIZONTAL DELTA	399	403	406	466	480 *	486	472	486	488		
HORIZONTAL	394	398	403	478	490 *	498	484	498	500		
SUSPENSION DELTA	569	579	585	615	629 *	635	621	635	637		
VERTICAL	9	9	8	8	8 *	12	12	16	18		
VERTICAL OFFSET (old & new)	9	9	8	8	8 *	12	12	16	18		
A-FRAME (old & new)	10	10	8	X	X	X	8 *	12	14		
HORIZONTAL DELTA	20	28	28	29	33 *	35	35	39	41		
HORIZONTAL	17	25	25	26	30 *	32	32	36	38		
SUSPENSION DELTA	28	36	36	37	41 *	43	43	47	49		

Notes:

- Standard designs are indicated by '*'
- Not applicable or component not used shown with 'X'
- An 'item' is a supplied assembly or stock item
- Bolting together two items is equivalent to an 'operation'

ITEM COUNTS, MATERIAL COST and LABOUR CONTENT for VARIOUS CONFIGURATIONS

TABLE 4.02



COMPARATIVE COSTS AND LABOUR CONTENT OF VARIOUS CONFIGURATIONS

FIGURE 4.22

"long-rod" insulators. The difference is significant as the decrease would bring it more into line on both labour content and material cost with the HORIZONTAL configurations.

The VERTICAL configurations are least expensive because they lack crossarms.

The labour content for bonding of spindles and securing earth wires is comparatively large because of the detail of the work required to bond all the metalwork on a structure. This work is however necessary in high-lightning areas and is a premium that has to be paid.

The major labour-content differences do not come from the earthing or bonding requirements but arise because of the number of separate components that have to be assembled to build up even a basic "bolts only" structure. These differences can be seen in the first column of Table 4.02.

CALCULATION AND EVALUATION OF THE COST PER KILOMETRE

The cost per kilometre is an inverse function of the maximum permissible span; the longer the span, the lower the cost. Should a configuration have a maximum permissible span of s (metres) then the number of spans per kilometre would be $1000/s$. The number of structures per kilometre would also be $1000/s$.

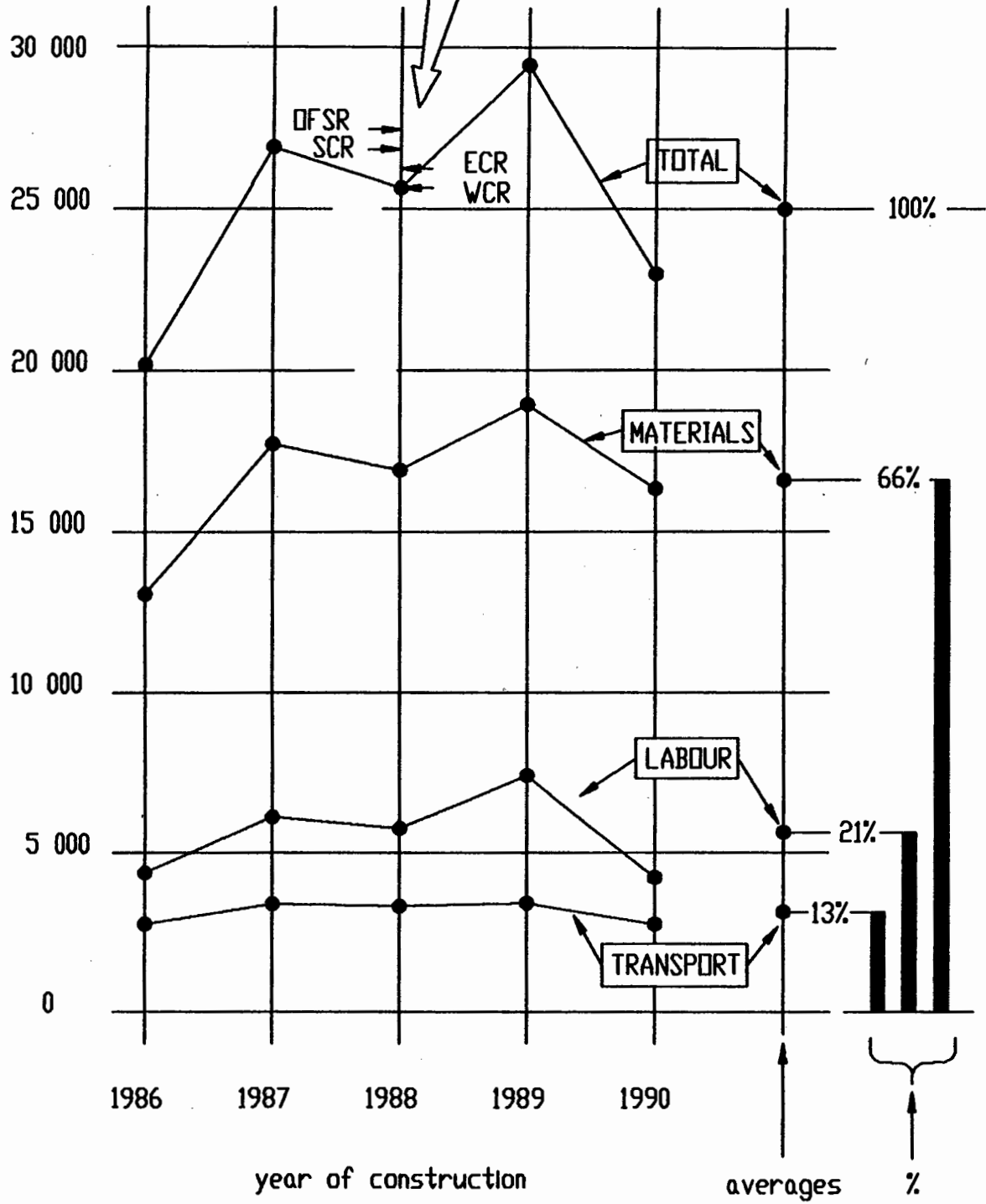
It has been possible to estimate material, labour and transport costs for the eight configurations. This has been done as follows:

Costing information (Eskom, 1991) for the construction of rural lines using the OLD A-FRAME for the five years, 1986 to 1990, is shown in Figure 4.23. Analysis of this data gives average percentages of 66% for material, 21% for labour and 13% for transport costs. The lines have been constructed using Mink conductor and average spans of 95m (or 10,5 structures per km).

Costs of lines built in other Regions have been included in the graph, for comparison. The costs of the OFSR lines, 50% of which were built by contractors, are on a par with Eskom's costs.

1991
Rand
per km.

Comparative data for four Eskom Regions for 1988.
 OFSR : Orange Free State Region
 ECR : Eastern Cape Region
 SCR : Southern Cape Region
 WCR : Western Cape Region



source: Eskom (1991)

ACTUAL COSTS FOR CONSTRUCTION OF 22kV DISTRIBUTION LINES
 WESTERN CAPE REGION, ESKOM (1986 to 1990)

FIGURE 4.23

The costing data for the OLD A-FRAME is calculated below:

standard structure (Table 4.02) :	R400
set of three conductor ties :	R19
total per structure :	R419
total for 10,5 structures (1km) :	R4 400
3 000m Mink conductor at R2,64/m :	R7 920
total of materials for 1km :	R12 320

This is equivalent to 66% of the total cost. The total cost for 1km of Mink line using the old A-Frame is thus R18 667.

Total cost of labour (21%) : R3 920 or R373 per structure.

Total cost of transport (13%) : R2 427 or R231 per structure.

These results now provide the basis for further calculations. The transport cost is assumed to be the same for all configurations. The labour cost is modified to include the cost of assembling the more complex configurations. It is calculated from available data (Eskom, 1991) that about 15% of the cost of labour (which includes erecting the structure) is spent in assembling an A-Frame. This R56 (15% of R373) is equated to the number of operations required (8) (Table 4.02) for the standard A-Frame structure. The additional labour costs are then calculated from the number of operations required for each configuration and added to the balance of R317 (85%) in order to make up the total labour cost for each configuration. It is assumed that there are no differences in labour costs for planting the poles and stringing the conductor for the various configurations. The stringing costs are not expected to differ because the main cost is that of running out the conductor over the kilometre length of line. Therefore the only differences arise out of the differing complexities of the configurations themselves.

The basic data required for Table 4.03, which is a summary of the results of this section, has been obtained from the calculated and graphed results. The maximum permissible span for a particular conductor and configuration is used to calculate the number of structures per kilometre and the total cost per kilometre. "Per structure" costs (including the cost of conductor ties) are added, multiplied by the number of structures per kilometre and the total added to the cost of the conductor.

CONFIGURATION FACTOR	VERTICAL	VERTICAL OFFSET (old)	VERTICAL OFFSET (new)	A-FRAME DELTA (old)	A-FRAME DELTA (new)	HORIZONTAL	HORIZONTAL DELTA	SUSPENSION DELTA
maximum allowable span (m)								
CLEARANCE of 5,2m	118	138+	150 *	194	191	209	196	164
STRESS IN POLE	275	267	267	233	240	233	240	254
Wind: 700Pa	211	201	201	178	183	178	183	194
	164	160	160	138	143 *	138	143	150
OVERTURNING	129	125	125	109	113	109	113	118
soil: 345kPa	99	95	95	83	86	83	86	89
Wind: 700Pa	76	74	74	65	66	65	66	69
CONDUCTOR SPACING 22kV	no limit	no limit	no limit	157 *	210	141	288	288
non-span-related factors								
Vs (kV) for a Vr of 22kV over 10km at I and 0,9 pf	24,97	24,97	24,95	24,97	24,96	24,98	24,97	24,98
	24,73	24,72	24,70	24,72	24,71	24,74	24,72	24,74
BIRD-FRIENDLY ?	24,63	24,63	24,58	24,61	24,61	24,64	24,62	24,65
	DK	DK	DK	DK	DK	NDT	NDT	DK
STRUCTURES / km based on limiting span	8,5	8,0	8,0	9,2	8,8	9,2	8,8	8,5
	10,1	10,5	10,5	12,0	11,6	12,0	11,6	11,2
	13,2	13,5	13,5	15,4	15,2	15,4	15,2	14,5
costs per standard structure (1991 RAND)								
STRUCTURE	378	378	378	400	400	490	480	629
LABOUR	373	373	373	373	373	527	548	548
TRANSPORT	231	231	231	231	231	231	231	231
total cost per kilometre including structure, ties, conductor, labour and transport (1991 RAND)								
name	cost							
FOX	2910/km	10	11 342	10 846	10 846	12 239	11 833	14 484
MINK	7920/km cost/	19	18 030	18 431	18 431	20 196	19 787	23 124
HARE	12150/km pole	32	25 535	25 839	25 839	28 104	27 897	31 862
								31 773
								14 963
								23 902
								33 030

Notes: Spans limited mainly by OVERTURNING. CLEARANCE and SPACING span limitations for some conductors.

SUMMARY OF THE ANALYSIS OF SOUTH AFRICAN PRACTICE : INCLUDING ESTIMATED COST PER km FOR EACH CONFIGURATION

TABLE 4.03

There has been a possible over-estimation of the cost of the labour associated with assembling the more complex structures. However, there is no doubt that more operations have to be carried out in order to assemble these structures. Assembly must therefore cost more than for a simpler structure.

On the other hand, there has been a possible under-estimation of the transport content of the costs for these more complex structures. The more components that have to be transported, the higher the cost. The stores facility (at the main centre and in the field) also has to be larger, to handle the larger number of different stores items.

4.3.8 DISCUSSION OF THE COMPARATIVE COSTS OF CONSTRUCTION OF RURAL LINES

The factors underlying the limiting spans (such as lack of clearance or overturning) will be evaluated in the next Section. This Part is restricted to a discussion of the data as presented in Table 4.03. The following general comments can be made with reference to this data.

The allowable span lengths are limited by overturning of the structures in most instances, due to failure of the foundation, for the given value of 345kPa for soil bearing capacity.

The average construction costs per kilometre for the selected eight configurations are R12 578 (Fox), R20 806 (Mink) and R28 735 (Hare). The percentage of the average costs due to the conductor alone are 23% (Fox), 38% (Mink) and 42% (Hare). Proportionately more of the total cost can be saved by reducing the cost per structure or the number of structures per kilometre for Fox compared to Mink compared to Hare conductor.

The lowest cost per structure (R992) is that for Fox conductor on the simplest structures (the VERTICAL and its variations) which consist of only a pole and insulators and minimal fittings. The highest cost (R1440) per structure is for Hare conductor on the most complex structure (the SUSPENSION DELTA). These costs include "structure", "labour", "transport" and "ties" costs per structure.

The HORIZONTAL and HORIZONTAL DELTA configurations, which have both been in use for a very long time, and are in use in similar forms in many countries (USA, UK, Australia, Brazil, etc), are more expensive than the VERTICAL, VERTICAL OFFSET or A-FRAME configurations. This is primarily because their higher component cost, component count and resulting higher labour cost. They suffer from one major disadvantage which is not cost-related: they are not bird-friendly structures. It is for this reason that Eskom has discontinued their use for rural distribution lines (Eskom, 1991).

The VERTICAL configuration differs from the other configurations in one major respect. The lowest conductor is attached comparatively further down the pole and, as a result, it has the shortest clearance span. The overturning moment is less for the same reason and it therefore

has the longest permissible span for Hare conductor (and hence also the lowest cost per kilometre).

There is only a minimal difference in the required sending end voltage and hence in the volt drop for these eight configurations. This factor is therefore not significant for the selection of the most economic structure.

It can be argued that the estimates for labour and transport costs are generally too high. However, the ranking of the structures by cost (individually or by cost per kilometre) would not change even if these two cost items were made the same for all configurations. The major differences in the cost per structure or per kilometre are due to two factors:

- the differences in the cost of the materials and
- the number of structures possible per kilometre due to specific span-limiting factors.

The cost of materials per structure can probably be reduced by an evaluation of each component with the aim of either eliminating it, replacing it with a less expensive component or by "doing it differently". For example, a nut plus locknut can be replaced by the cheaper combination of a nut plus lockwasher and a pair of glass disk insulators can be replaced by a single longrod insulator. However, the mechanical and electrical integrity and operational life of the structure as required by the operational conditions should not be adversely affected by the changes made.

4.4 EXAMINATION OF THE FACTORS LIMITING THE USEABLE SPAN

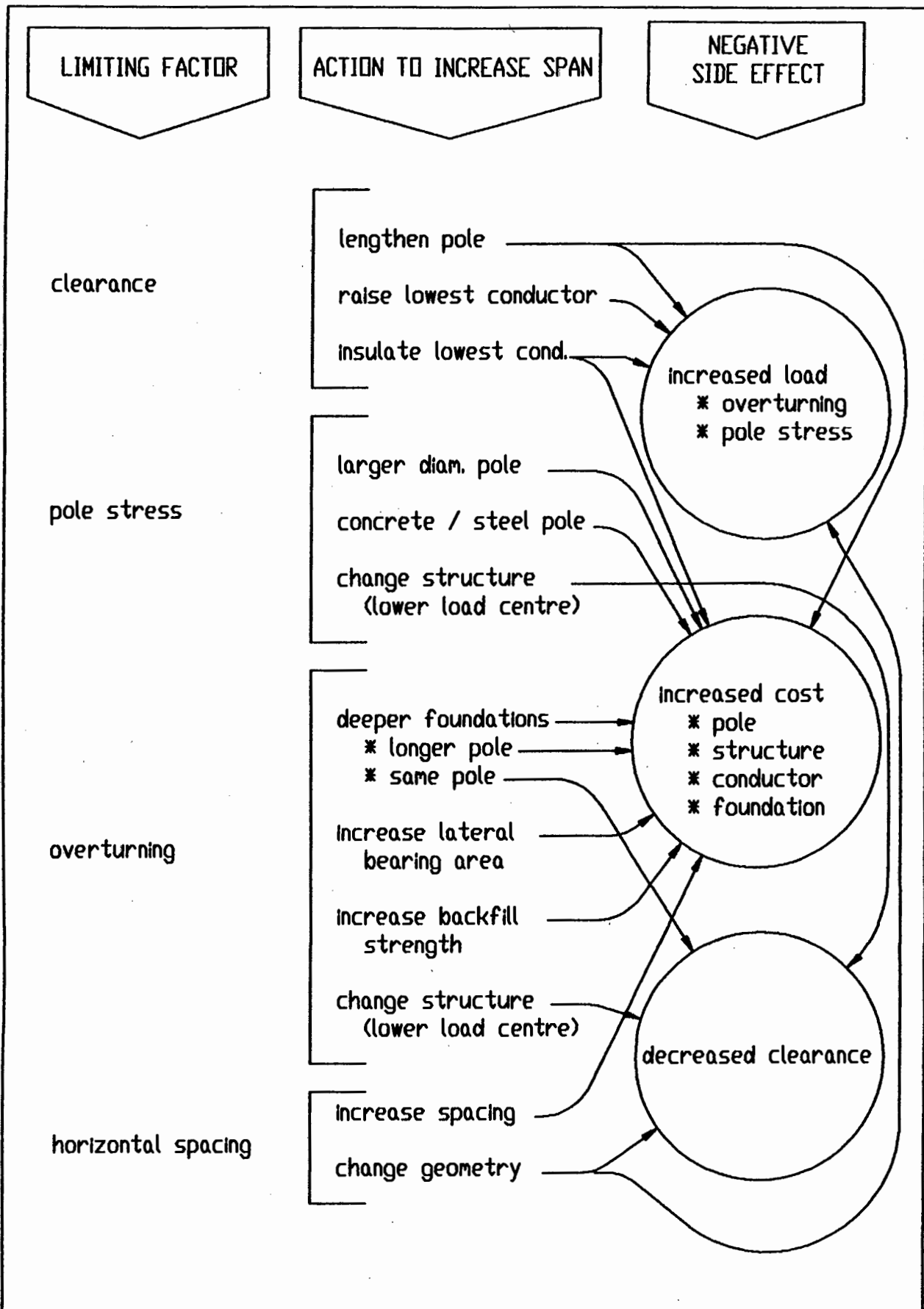
The eight selected standard designs, as used throughout Eskom, were analysed and discussed in detail in the previous Section. Their geometry and components and the pole used were considered as constants for the purposes of analysis and comparison. The analysis showed that the maximum useable span for a particular configuration was limited by a factor that could be unique to that configuration. This maximum useable span is inversely proportional to the minimum number of structures that have to be used per kilometre of line. The number of structures per kilometre is proportional to between 77% and 58% of the overall cost of the line.

The aim of this Section is to examine how, and to what extent, the maximum useable spans can be extended.

There are four factors that limit the maximum useable span of a line: clearance, pole stress, overturning and horizontal conductor spacing.

In the discussion below the load (which is a function of the wind pressure as specified in the MOS Act (1983) and which affects pole stress and overturning) is assumed to be constant. Of the four factors given above only one, overturning, is a function of a variable external to the pole structure itself, namely the soil bearing capacity.

Table 4.04 lists the four factors and the action that can be taken to increase the span. These actions are referred to their negative side effects. The main benefit of increasing the span is to decrease the overall line costs. The negative side effects either decrease this benefit directly (by increasing costs) or negate the benefit of the increase in span by worsening the effect of one or more of the other factors.



NEGATIVE SIDE EFFECTS OF INCREASING THE SPAN

TABLE 4.04

Examples:

If it is assumed that the maximum useable span is limited by clearance then one option would be to insulate the lowest conductor (if this were a legal exemption granted in terms of the MOS Act (1983)). The major penalty would be an increase in cost of about R1 100 per kilometre for XLPE-covered Fox conductor. The overturning load would be increased by a small amount due to the conductor being thicker overall. The benefit would depend on what the permitted clearance for using the insulated conductor would be. A concession to 5,0m would increase the useable span to 129m and save about R700 per kilometre for a VERTICAL configuration using Fox conductor.

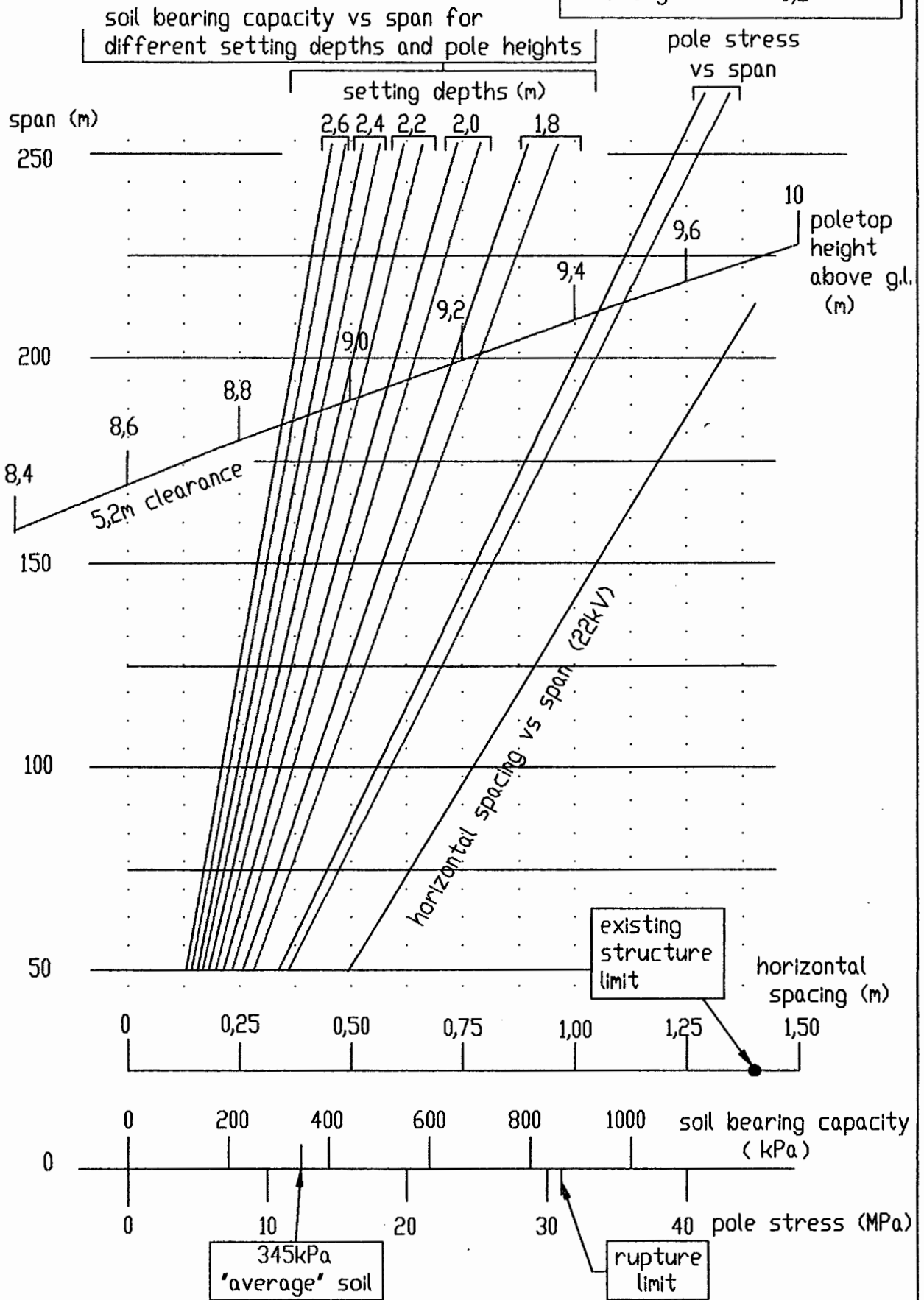
For a second example overturning is taken as the limiting factor. An option to improve this limit is to have a deeper foundation with either the same or a longer pole. The negative side effects are increased costs and decreased clearance.

The above comments are not sufficiently quantitative. It is also not straightforward to get estimates of cost increases or clearance decreases. It was with the specific purpose of establishing better estimates that Figure 4.24 was developed. This Figure is a combination of the graphs for each of the four limiting factors shown previously and presented here for one structure (the NEW A-FRAME) and one conductor (Mink). The nomogram has been drawn for the MOS Act (1983) design limits of 700Pa wind and 5,2m (22kV) clearance. The same type of nomogram can be made for any structure/conductor combination. Five different pole setting depths and two different heights of the poletop above ground level provide a range of factors which enable span lengths to be changed and the consequences and corrections to be analysed.

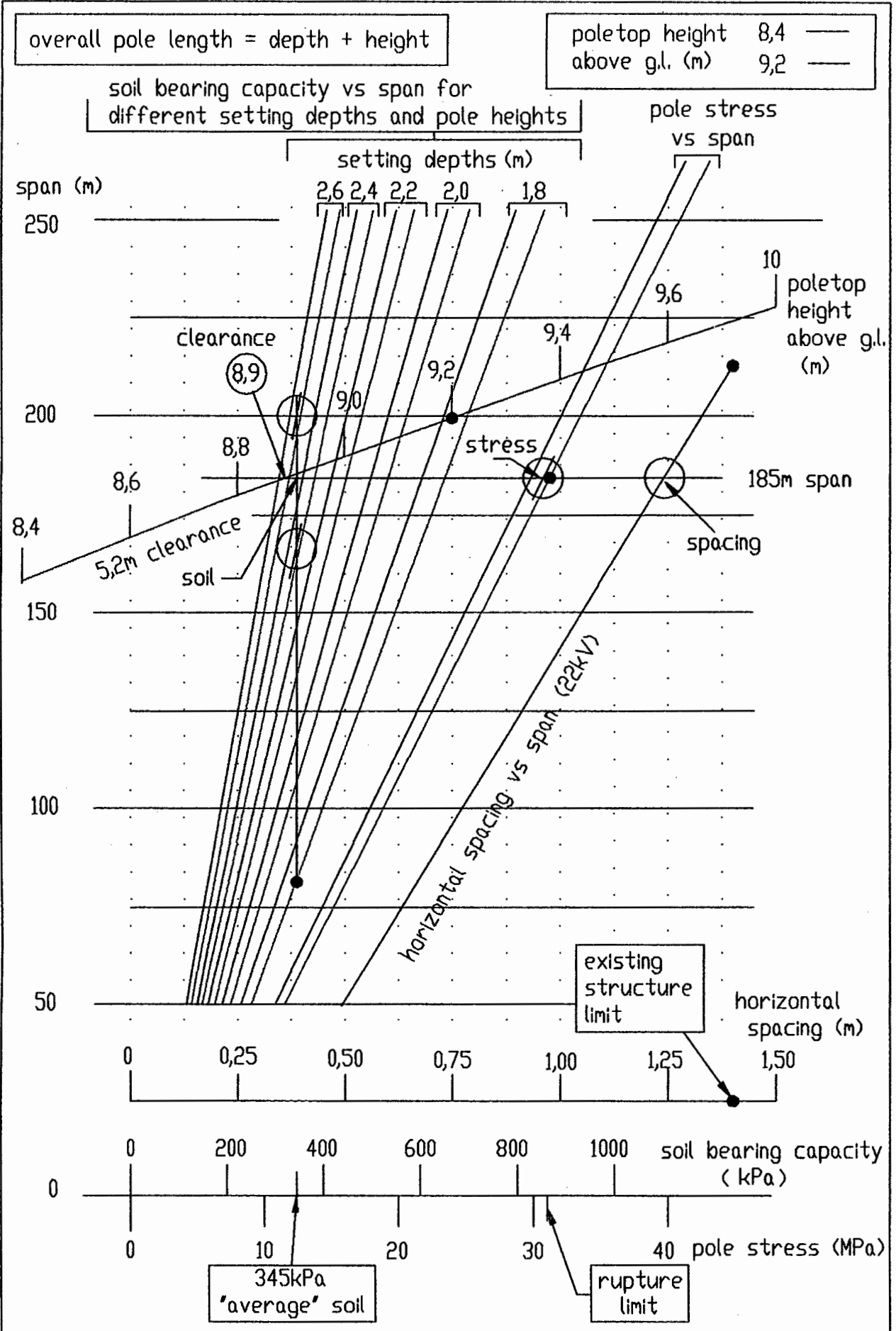
Figure 4.25 illustrates the use of the nomograph to explore the factors limiting the span of the NEW A-FRAME configuration on a woodpole under the MOS Act (1983) conditions and using Mink conductor. The first operation is to look at the span limits of this particular configuration. These are (from Table 4.03): 213m for conductor spacing, 200m for clearance, 185m for pole stress and only 80m for soil bearing capacity. These points have been plotted on Figure 4.25 as large dots. The maximum useable span is clearly the short span of 80m due to the limit of the "average" soil bearing capacity being reached. The other three limits are fairly close to one another. The first option is to improve the strength of the foundation so that the limiting span is at least 185m (the limit for pole stress).

overall pole length = depth + height

pole height above g.l. (m) 8,4 —
9,2 —



GRAPHS OF SPAN-LIMITING FACTORS FOR THE NEW A-FRAME WITH MINK CONDUCTOR UNDER 700Pa WIND LOAD
FIGURE 4.24



GRAPHS OF SPAN-LIMITING FACTORS FOR THE NEW A-FRAME
 WITH MINK CONDUCTOR UNDER 700Pa WIND LOAD
 ILLUSTRATING HOW THE MAXIMUM USEABLE SPAN CAN BE INCREASED
 FIGURE 4.25

The horizontal line through this point on the stress graph intersects the clearance graph at approximately 8,9m. This is the required height of the poletop above ground level for a 5,2m clearance. This pole height lies between the two stress graphs (drawn for 8,4m and 9,2m) and the stress in the pole is just below the rupture limit.

A vertical line at the "average" soil limit will intersect the setting depth lines to give spans that will not cause the soil bearing capacity to be exceeded. A pole with a setting depth of 2,6m will give a span of about 190m for an above-ground poletop height of 9,2m. The poletop height of 8,9m for the clearance limit can be interpolated between the soil graphs, as for the stress graphs. The maximum span is then given as 200m (upper circle). Similarly the 8,9m height line for a 2,4m setting depth can be drawn to give a maximum span of 165m. Interpolation of the intersection of the 185m span line and the 345kPa soil line gives a pole setting depth of 2,5m. The total pole length is then 11,4m (2,5m + 8,9m).

The new maximum useable spans are: 213m for conductor spacing, 185m for clearance, 190m for pole stress and 185m for soil bearing capacity. This is clearly very nearly an optimum design.

The horizontal conductor spacing can be decreased to 1,25m in order to bring the spacing limit in line with the others. This will also have the benefit of a saving in material for the construction of the crossarm and also compensate for the increased cost of the (longer) pole.

Any further increase in span would require that all the factors be changed together. The most drastic change is that a change of pole material (or the selection of larger diameter poles) is required. The option that will be considered is to change the pole material to concrete.

Concrete poles suffer from two major disadvantages. They are considerably heavier. (An 11m spun concrete pole has a mass of 1020kg compared to a woodpole which has a mass of about 200kg.) An 11m concrete pole costs about R470 compared to about R170 for a creosoted pine pole.

The advantages of concrete poles are greater strength, (about twice that of a pine pole), faster availability (a month for a concrete pole compared to twenty years for a pine pole) and closer control of the strength parameters.

Concrete poles are also considered to be aesthetically more pleasing because of the regular shape and light colour and are cleaner to handle.

Another, rather more subtle advantage, is that concrete pole have a larger taper and therefore larger groundline and foundation diameters. This means that they are inherently more resistant to overturning. Concrete poles can also have a "cast-in" shape advantage in that pre-stressed poles could have a flat face in the direction of the load, giving them a nearly 18% better resistance to overturning because of the applicable shape factor (1 instead of 0,85) used in the formula.

Figure 4.26 has been drawn to present a case for the use of concrete poles in the construction of rural lines.

Once the woodpole stress limit can be passed the next limit is that due to the horizontal spacing of the conductors. This is a "soft" limit in that the spacing, and hence the maximum useable span, can be increased (within the mechanical stress limits of the crossarm structure) by lengthening the crossarm.

The maximum useable span for the horizontal conductor spacing on the NEW A-FRAME is 213m. The minimum pole height above ground level which gives 5,2m ground clearance for this span is 9,5m.

The setting depth for "average" soil for this pole height for the pole to withstand overturning should be 2,2m. The overall pole length required is then 11,7m (9,5m + 2,2m).

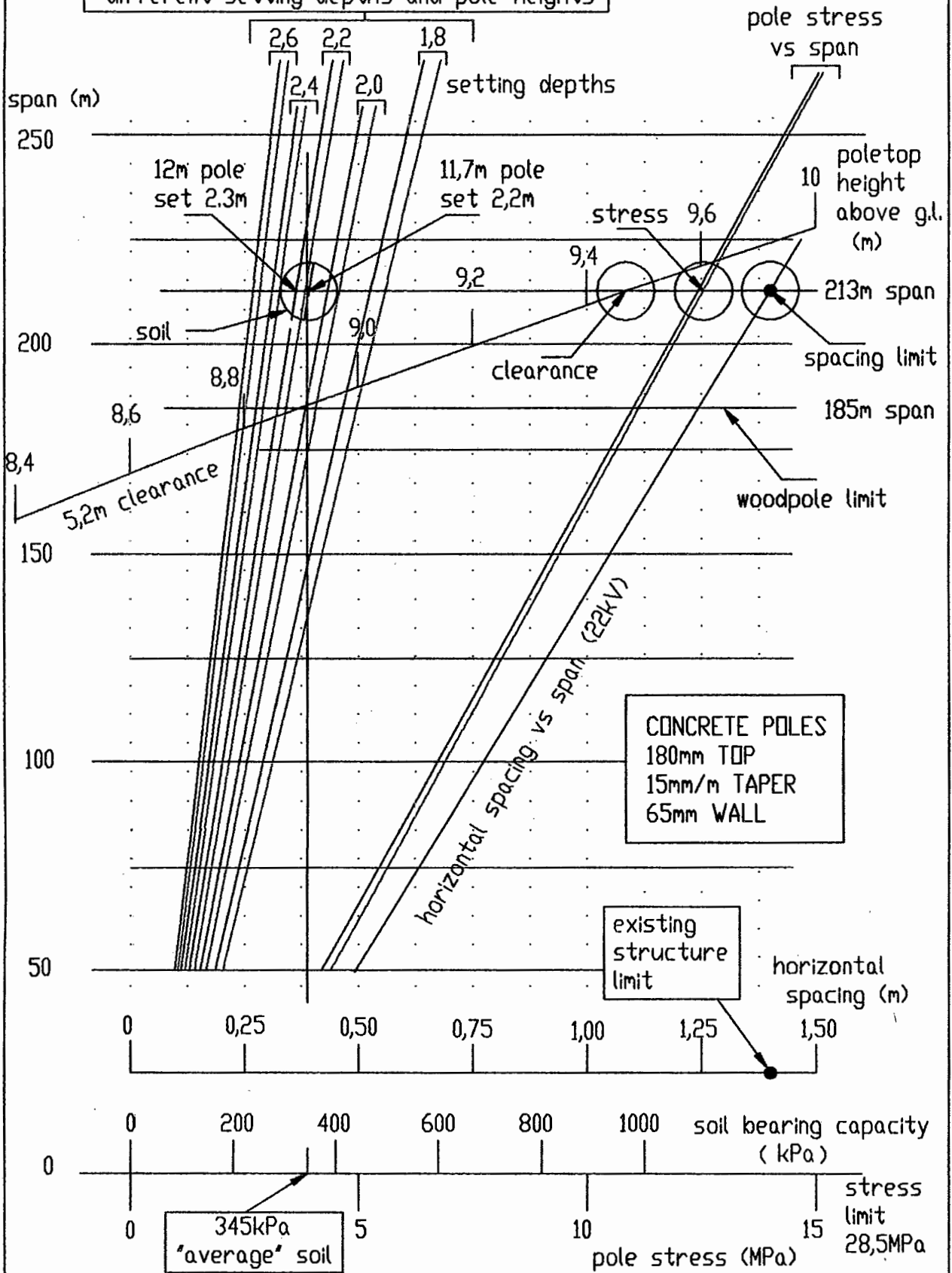
However, 12m is a standard length for a concrete pole. For the same setting depth of 2,2m the poletop height above ground level would be 9,8m and the required soil bearing capacity would be exceeded. Changing the depth to 2,3m would change the pole height to 9,7m above ground level. The required soil bearing capacity would be below the limit and therefore acceptable.

Graphs of the costs/km of woodpole and concrete pole lines are shown in Figure 4.27. The overall cost comparisons of the three structures is given below.

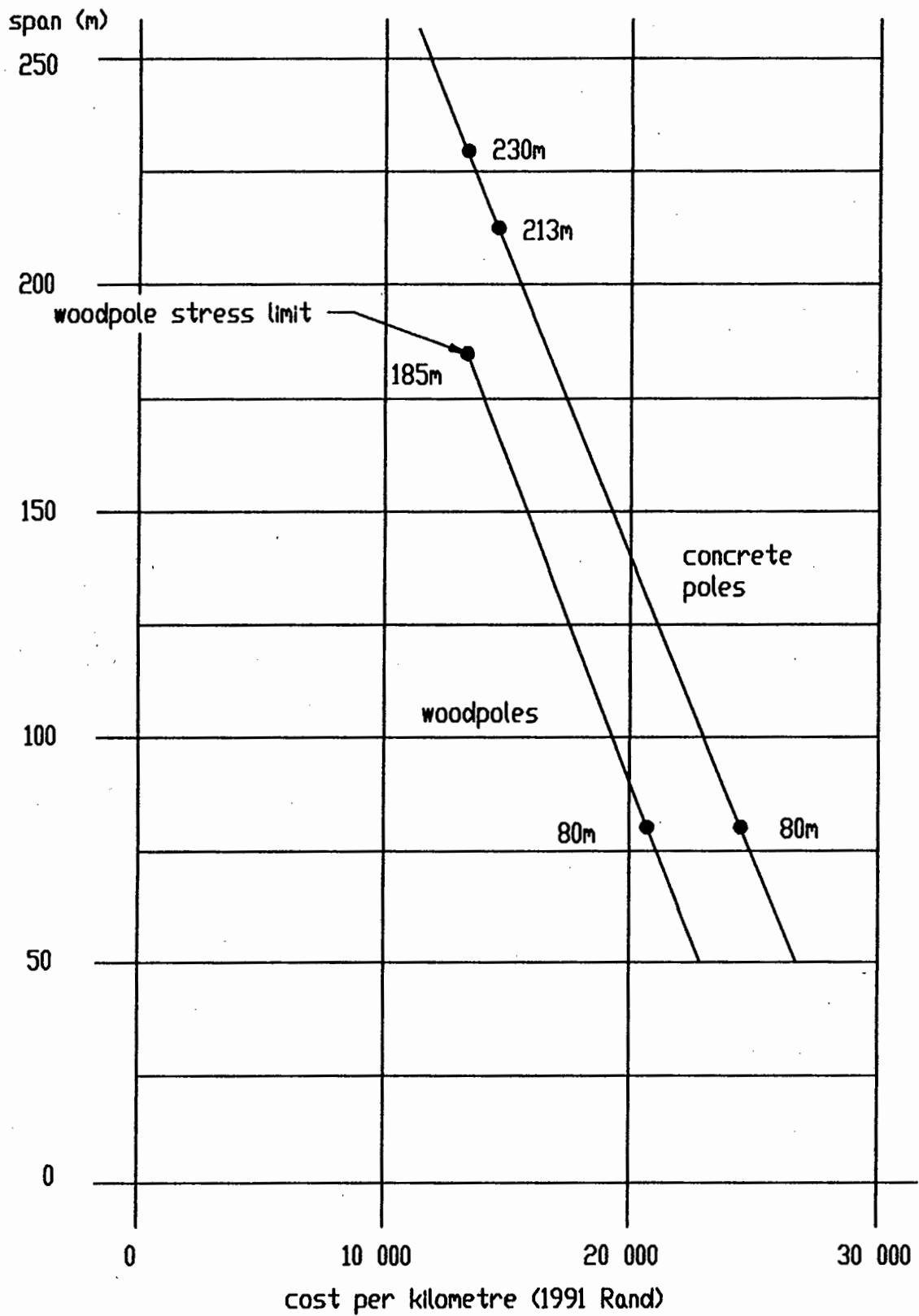
overall pole length = depth + height

pole height above g.l. (m) 8,4 —
9,2 —

soil bearing capacity vs span for different setting depths and pole heights



GRAPHS OF SPAN-LIMITING FACTORS FOR THE NEW A-FRAME WITH MINK CONDUCTOR UNDER 700Pa WIND LOAD ILLUSTRATING HOW THE MAXIMUM USEABLE SPAN CAN BE INCREASED
FIGURE 4.26



COST PER KILOMETRE FOR MINK CONDUCTOR LINE USING NEW A-FRAME STRUCTURE
 COMPARISON OF COSTS FOR WOODPOLES AND CONCRETE POLES
 FIGURE 4.27

Pole Data	(m)	span /km	spans /struct. (R)	cost (incl. cond.) (R)	cost/km
"standard" 11,0m pole 1,8m set	80	12,5	1 023	20 707 (Note 1)	
woodpole 11,4m pole 2,5m set	185	5,4	1 050	13 590 (Note 2)	
concrete 12,0m pole 2,3m set	213	4,7	1 423	14 608 (Note 3)	

- Notes:
1. Data as presented in Table 4.03
 2. Estimated additional cost for a longer pole.
 3. Additional R400 per pole for concrete.

The most obvious item to note from the above table is the radical decrease in overall cost theoretically possible by the simple expedient of digging a deeper hole. The costs per kilometre for a woodpole line compared to a concrete pole line are within R1 000 of each other despite the large cost penalty per pole for using concrete. The increase in pole length is directly due to the requirements for adequate clearance and for the increased setting depth.

The major limit of any of the exercises to increase the span is the limit of adequate soil bearing capacity. The comparisons made within the limitations of the theory do show some ways of probing the structural and cost limits of structures for rural lines. Some of the limits are perceived to be "hard" and unchangeable. There are, however, usually some method or technique or change of material which make it possible to extend the limits economically.

The nomogram for a particular structure and conductor (such as shown in Figures 4.24 to 4.26) can of course be used as a practical design tool. The vertical line for the soil bearing capacity is then drawn to reflect the results of soil tests.

Eskom built an average of about 10 000km of lines at 22kV and below per year from 1985 to 1990 (Eskom, 1990). The construction cost of these lines, at R20 000/km (in 1991 Rand), was about R200 million per year.

CHAPTER 5

CONCLUSIONS

This Chapter is divided into three Sections, each discussing a group of results from this research.

The first Section discusses the direct results of the research, the aim of which was the comparison of poletop structures for rural lines at 11kV and 22kV.

The second Section takes a look at the indirect results of the research. The topics covered include the peripheral subjects of similar research and codes of practice.

The last Section describes areas where further research is needed. The most important area is the investigation of foundations for single-pole structures in theory and practice.

5.1 DIRECT RESULTS OF THE RESEARCH

The following comments are made and conclusions drawn from the analysis and evaluations carried out:

Comparison of the Theories

Seven aspects of the theory of the design of lines were discussed.

These aspects were:

1. spans, sags and tensions
2. pole strength
3. foundation strength
4. conductor spacing
5. lightning effects
6. electrical losses
7. environment / wildlife

Spans, sags and tensions and pole strengths are the essentially mechanical aspects of the theory and are thoroughly understood and known. The theories are common to all users. The differences in application arise from the use of different limiting conditions. These include statutory conditions (such as clearance), stress limits for woodpoles and temperature and tension limits for conductors.

Foundation design theories provide a number of diverse and conflicting formulae. The most difficult part of the calculation in practice is obtaining the value for the soil bearing capacity that should be used. The current USA practice does not call for the design single-pole foundations, relying instead on a fixed setting depth for all strength classes of poles. A comparative evaluation of the formulae was not made as an in depth study of soil mechanics is required and that was considered to be outside the scope of this thesis.

The theories underlying conductor spacing are all empirical in origin. Adaptations based on practical experience have decreased the required spacings. Vertical separations can be as close as the phase-to-phase clearance where shedding of snow loads is not of concern, as is generally the case in South Africa.

Techniques to limit the disruption and damage caused by lightning are limited to those areas of higher lightning intensity towards the eastern parts of South Africa. Use of a 300kV BIL appears currently to be the best option for these areas. The cost of material and labour for "lightning-proofing" line structures used in these areas is the main cost difference between them and structures in non-lightning areas.

Electrical losses are not significant as a means of measuring differences between configurations.

The impact of rural electricity distribution structures on the environment, and particularly on wildlife, will have an even greater impact on design in future. Structures which pose a risk are no longer being used for the construction of rural lines. Coincidentally these structures have also been shown in the analysis to have a comparatively higher cost. Existing dangerous structures will have to be assessed with a view to local (habitat or flightpath) bird-proofing or total replacement. Clearly, this may have a major effect both on project and maintenance costing.

Foundation Failure

This tends to be the main limiting factor for all configurations in achieving a long maximum span. The theory used (that of the SAIEE Code of Practice (SAIEE, 1966)) indicated that the foundations may fail. The fact that very few lines fail in practice indicates that the theory or, more correctly, the formula is suspect. This aspect of the design theory needs evaluation and testing to check its validity or error.

Pole Classification

The strength of the pole is a direct function of its ground-line diameter. The pole can not be loaded to its full capacity unless either the foundation (or soil) is strong enough or the pole is set deep enough. Woodpoles are currently supplied against the specification of a top diameter but the ground-line diameter is not specified. The grading of poles into classes, which depend on the specific timber species and the ground-line pole diameter (as is REA practice), can be

used with benefit in South Africa. The pole should also be marked with its optimum setting depth so that the full strength of the pole can be utilised in average soil.

Maximum Useable Spans

The maximum useable spans can be increased considerably by challenging the factors limiting the spans. The optimum limit occurs when all factors (clearance, pole strength, horizontal spacing and foundation strength) have effectively the same limiting span. The main limit of foundation strength can be passed by digging deeper foundations. The maximum useable span for a woodpole with a 160mm diameter top is in the region of 185m, at which span the limit in the pole stress is reached. The actual maximum span depends on the poletop structure used. Beyond 185m concrete (or steel) poles would have to be used if single-pole structures were to be built. The initial higher cost of concrete poles would make it economic to use concrete poles for spans only in excess of about 230m, under present circumstances of wood and concrete pole cost and availability. For spans of between 185m and 230m it would be cheaper to use more shorter woodpole spans. The cost is about the same if woodpoles at 160m spans or concrete poles at 213m spans are used.

A "maximum wind loading span", equivalent to a span limited by pole stress in this research, is used in the literature. A figure of about 180m is quoted in BS1320 (1946) for a three-phase line using a 10,4m pole and a conductor smaller than Fox. REA (1982) relates the maximum span to only the pole strength. The load, of course, depends on the wind pressure and the area exposed to it. Generally the literature does not quote limiting spans for a structure for low-voltage (11kV and 22kV) lines. This is probably due to the fact that there are too many variables (particularly in the USA), such as structure, pole type and length and conductor size. Each combination is treated as a unique design exercise for a particular line.

The standardisation taking place within Eskom at present will make it feasible to produce nomograms, such as in Figures 4.24 to 4.26, for each structure/pole/conductor combination. The unknown of the soil bearing capacity can be taken into account by allowing for different setting depths (as one method) as used in the above-mentioned Figures.

A point worthy of mention is that there are other mechanical strength limits which have to be taken into account when the ultimate structural limits of the line are probed. The strength of

the "minor components", such as the fasteners and fittings that go to make up the complete structure, has also to be considered.

Comparative Costing of Structures

The exercise of comparing costs highlights several factors which affect the cost of a structure. In broad principle, the more components a structure uses, the higher the cost of the structure. The cost of the material for the HORIZONTAL DELTA configuration is 20% more than the cost of the material for either of the A-FRAME configurations. (Both configuration types are geometrically similar.) More components not only cost basically more but also cost more to assemble and to store.

The cost comparisons also show that the new standards that Eskom is using are the inherently low-cost structures of those analysed.

5.2 INDIRECT RESULTS OF THE RESEARCH

The indirect results arise out of matters that are outside the main object of the research.

Similar Research

As far as can be established no similar research, either as regards background or scope, has been published or referred to in the literature. Similar detailed comparisons of structures have not been done, nor has the broad theory been examined in detail.

"Overdesign" of Structures

The overall perception of the design of rural lines is that there are very few structural failures in practice. The failures that are mentioned in the literature are generally failures of the foundations in that the poles lean somewhat from the vertical. Storms have been known to damage multi-conductor telephone lines and even high-voltage transmission lines without seriously affecting nearby rural feeders.

The implication of the above comments is that rural lines appear to be overdesigned. The safety factors and tolerances are so large that even the lines not built strictly to the design do not fail.

Lines are supposedly designed for the ground clearances as laid down in the MOS Act (1983) for a conductor temperature of 50°C. In practice the clearance is often more than that required and, in addition, the conductor very seldom reaches a temperature of 50°C.

Should designs be pushed close to their optima then the construction of the lines (methods, equipment and practice) will have to be monitored more closely. Problems are already being experienced in Eskom where small diameter conductors (such as Fox) on long spans are overtensioned on erection. Failure is due either to vibration-induced fracture or to excessive tension at very low temperatures occurring after erection. Inaccurate tension or temperature

measurement during erection could be the underlying cause. Vibration dampers should also have been installed.

It is because it is perceived that these tolerances are too wide that EPRI and Eskom have (separately) embarked on the development and application of probabilistic design methods. The development of such methods however requires an accurate and detailed reporting and testing information system as probability studies cannot be done without good historical statistics.

Standardisation

The use of standard structures consisting of standard components will have great cost benefits for the construction of rural lines. Fewer stores stock items will need to be held, resulting in reduced storage and handling costs. There is, however, the danger of a supplier of standard components becoming monopolistic, to the detriment of the cost. Alternative standard components (such as insulators) should be available for this reason.

Codes of Practice

Certain references, particularly Codes of Practice, have, in some instances, been difficult to use or have been "incomplete". The South African line design information is not consolidated into one complete document. This should be done.

It is recommended that there should be two sections to a code of practice. The contents of these two sections are outlined below. The recommendation is based on the experience gained from using several codes of practice while doing this research. This layout for a code of practice is typical of those from Australia and USA for rural line design.

Section 1: Design Theory and Legislation

This section is a general design section relating to the electrical and mechanical aspects of the design. It should contain data pertinent to the materials, safety factors, legal requirements,

foundations, design formulae, conductor data, etc. The document should be updated frequently.

Section 2: Construction Data

This section illustrates structures fully and provides bills of materials. It would also contain data about the limitations (such as maximum useable spans) for the structures it details. This information is relevant only to the particular region in which the lines are to be constructed and operated.

Section 1 should be a National Standard drawn up by the South African Bureau of Standards and published and maintained by them. The production of the standard would be based on contributions and work by representatives of, for example, Eskom, the municipalities, consultants, contractors and suppliers.

Section 2 would be produced by the individual authority using it, such as Eskom or a major consulting firm or municipal association.

5.3 FURTHER RESEARCH

There are two major areas where further research needs to be carried out into South African aspects of rural line design:

Pole Ultimate Fibre Stress (Modulus of Rupture)

There is uncertainty about what value to use for the design modulus of rupture. There is also uncertainty about the mechanical load testing of poles to a test value of even 55MPa as fibres are broken during this testing process. (Despite these misgivings, however, very few sound poles fail in service due to wind overload.)

Foundation or Soil Bearing Capacity

An investigation needs to be done into the validity or error of the SAIEE (1966) formula for foundation design and also its comparison to the other formulae for foundation design referred to in this thesis.

In addition, any of the foundation design theories require a value for the soil bearing capacity. An inexpensive means of obtaining this value needs to be found. The major benefit would be that the uncertainty of the design can then be reduced.

REFERENCES

- Aberdare, 1990. Overhead aluminium conductors. Edenvale: Aberdare Power Cables.
- ACTEA, 1984. Branch instruction No. 4: Overhead lines - construction and maintenance. Canberra: Australian Capital Territory Electricity Authority.
- Andersson, L., Svensson, S., Nylund, J. & Regner, L. 1989. New types of mv distribution overhead lines and loc-analysis as a method for selecting type. CIREC, 10th International Conference on Electricity Distribution; Cables and Overhead Lines. London: Institute of Electrical Engineers. p.185-206.
- Banks, C. H. et al. 1977. The mechanical properties of timbers with particular reference to those grown in the Republic of South Africa. Bulletin No 44. Pretoria: Forestry Research Institute, Department of Forestry.
- Basson, M. M. 1990. Comments on installed South African designs. Private communication. Design Section. Bellville: Eskom, Western Cape Region.
- Bowles, J. E. 1977. Foundation analysis and design. 2nd edition. New York: McGraw-Hill.
- BS 1320, 1947. High voltage overhead lines on wood poles for line voltages up to and including 11kV. London: British Standards Institution.
- Butterworth, S. 1954. Electrical characteristics of overhead lines. London: Electrical Research Association.
- Chance, A. B. 1982. Line hardware catalogue. Centralia: A. B. Chance Company.
- Designing bird friendly powerlines. Elektron, November 1990. Johannesburg: South African Institute of Electrical Engineers.
- EPRI, 1981. Probability based design of wood transmission structures. vol. 1, 2, 3. Project 1352-1. Final Report. Palo Alto: Electric Power Research Institute.

EPRI, 1987. Probability based design of transmission line structures. vol. 1, 2, 3. Project 1352-2. Final Report. Palo Alto: Electric Power Research Institute.

ESAA, 1990. Design and Maintenance of Overhead Distribution and Transmission Lines. Sydney: Electricity Supply Association of Australia.

ESI, 1974. 11kV Single circuit overhead lines of light construction on wood poles. Electrical Supply Industry Standard 43-10. London: Electricity Supply Industry.

Eskom, 1974. Substation layout design guide. Eskom internal publication. (Insulation and Clearances, Section SLDG2). Johannesburg: Eskom.

Eskom, 1989a. Appropriate technology for electrical reticulation in developing countries. Johannesburg: Eskom.

Eskom, 1989b. Statistical Report. Johannesburg: Eskom

Eskom, 1990. Annual report. Johannesburg: Eskom

Eskom, 1991. Line construction : Internal reports and statistics. Private communications. Bellville: Western Cape Region, Eskom.

Freeman, P. J. 1974. Electric power distribution. 2nd edition. London: Harrap.

Freileitungsbau bis 30kV. Elektrotechnik Nr. 5, 6, 7, 8 1984. (in German) (Poles and tower erection for overhead lines up to 30kV.) Switzerland.

Gaunt, C. T., Britten, A.C. & Geldenhuys, H. C. 1989. Insulation co-ordination of unshielded distribution lines from 1kV to 36kV. Johannesburg: South African Institute of Electrical Engineers.

Glover, J. D. & Sarma, M. Power systems analysis and design. Boston: PWS Publishers.

Gracey, G. C. 1963. Overhead electric power lines. London: Benn.

Kent, B. 1990. Reasons for the use of steel poles in the Northern Territories. Private communication. Darwin: Power and Water Authority, Northern Territories, Australia.

Krogh, P. M. D. 1966. Use of chemically impregnated wooden poles for telephone and power transmission lines in South Africa. Bulletin No 42. Pretoria: Forestry Research Institute, Department of Forestry.

Lay, M. J. 1990. Distribution and transmission planning. Course presented at Eskom College 14 - 16 May 1990. Johannesburg: Eskom.

Ledger, J. 1988. Eskom Bird Identification Guide. Johannesburg: Eskom.

Lehtinen, H., Lehtinen, I. & Hinkkuri, A. 1989. Research on covered medium-voltage overhead lines in Finland. CIREN, 10th International Conference on Electricity Distribution; Cables and Overhead Lines. London: Institute of Electrical Engineers. p.179-184.

Macey, R. E. & Dickson, D. 1987. Designing distribution lines for low cost and high reliability. SAIEE Conference on Power Distribution and Reticulation. Johannesburg: South African Institute of Electrical Engineers. Session 6, paper 1.

McCombe, J. & Haigh, F. R. 1966. Overhead line practice. London: MacDonald. p.52-55.

Morecombe, W. 1929. Overhead power lines. London: Chapman.

MOS Act, 1983. (Machinery and Occupational Safety Act, Act No. 6 of 1983) Electrical Machinery Regulations: 13. Earthing, 14. Supports, 15. Clearances of power lines. Johannesburg: Lex Patria

NESC, 1987. (National Electrical Safety Code) ANSI C2 New York: Institute of Electrical and Electronics Engineers.

Nigol, O. & Buchan, P. G. 1981. Conductor galloping. Parts 1 and 2. IEEE Transactions on Power Apparatus and Systems, Vol PAS 100 No 2 Feb 1981 p.699-720.

Nolasco, J. F. 1989. Lecture notes for an MSc course at UCT: EEE 573Z Power Transmission Line Design. chapter V, XI. Belo Horizonte, Brazil: Companhia Energetica de Minas Gerais.

PAWA, 1989. Overhead Line Manual. Darwin: Power Directorate, Power and Water Authority, Northern Territories, Australia. vol. 1.

Ratkowski, J. J. 1963. Experiments with galloping spans. IEEE Transactions on Power Apparatus and Systems. vol. 82, p.661-669.

Ratkowski, J. J. 1968. Factors relevant to high-amplitude galloping. IEEE Transactions on Power Apparatus and Systems. vol. 87, no. 6, p.1385-1396.

REA, 1982. (Rural Electrification Administration)
Mechanical design manual for overhead distribution lines. Washington: REA, United States Dept. of Agriculture. chapter II, p.19-20.

REA, 1988. (Rural Electrification Administration)
Specifications and drawings for 7.2/12.5kV (also for 14.4 and 24.9kV) line construction. Washington: REA, United States Dept. of Agriculture.

Roberts, 1978. Birds of South Africa. (revised by G. R. McLachlan and R. Liversidge.) Cape Town: John Voelker Bird Book Fund.

SABS 0160, 1980. The general procedures and loadings to be adopted for the design of buildings. Pretoria: South African Bureau of Standards. p.29-71.

SABS 0163, 1980. Code of practice for the design of timber structures. Pretoria: South African Bureau of Standards.

SABS 339, 1951. Standard specification for creosoted wooden telephone, telegraph, electric light and power transmission poles. Pretoria: South African Bureau of Standards.

SABS 753, 1964. Standard specification for wooden power transmission poles and crossarms. (as amended 1965) Pretoria: South African Bureau of Standards.

SABS 753, 1982. Standard specification for pine poles and crossarms for power transmission, low voltage reticulation and telephone systems. Pretoria: South African Bureau of Standards.

SABS 754, 1982. Standard specification for eucalyptus poles and crossarms for power transmission, low voltage reticulation and telephone systems. Pretoria: South African Bureau of Standards.

Sadurski, K. L., Smith, J. M. & Britten, A. C. 1989. Some aspects of the design of medium voltage woodpole structures from a lightning point of view. Elektron. July 1989. Johannesburg: South African Institute of Electrical Engineers.

SAIEE, 1966. Code of practice for overhead transmission lines for conditions prevailing in South Africa. Johannesburg: South African Institute of Electrical Engineers.

SBR, 1970. Standard Building Regulations. Government Gazette No. 2894. Pretoria: Government Printer.

Schepers, M. G. & Good, M. L. 1985. Eliminating short guy leads through better pole embedment. 1985 IEEE Rural Electric Power Conference. Paper 85 D1.

SECV, 1987. Overhead line manual. Melbourne: State Electricity Commission of Victoria, Australia.

SECWA, 1990. Overhead line design manual. Perth: State Electricity Commission of Western Australia. Section 7. 22kV Constructions.

Standard Handbook for Electrical Engineers, 11th edition. edited by D. G. Fink and H. W. Beaty. New York: Mc Graw-Hill. Section 14, p.76-79, p.95-101.

Stein, J. 1988. A unified theory for the design of pole foundations. International Conference on Overhead Line Design and Construction: Theory and Practice (up to 150kV). London: Institute of Electrical Engineers. p.32-35.

Structural stability and reliability of various designs of medium-voltage overhead-line constructions by E. Brandt, N. Becker, H. Pohlmann, S. Fuchs, H. J. Fiss, H. Muller, W. Booz and G. Thierauf. 1989. CIREN, 10th International Conference on Electricity Distribution; Cables and Overhead Lines. London: Institute of Electrical Engineers. p.173-178.

Thomas, E. S. 1978. Line design factors for severe coastal environments. 1978 IEEE Rural Electric Power Conference. paper 87 C2.
p.1-8.

Thomas, P. H. 1928. Formula for minimum horizontal spacing. Trans. AIEE. vol. 47, p.1323-1328.

Van Rooyen, D. C. & Hugo, W. M. J. 1983. Purchasing Management. London: Addison-Wesley.

Winants, V. & Reiz M. 1970. Conductor galloping on overhead lines. CIGRE International Conference on Large Electric Systems at High Tension 1970. vol. 1, paper 22-06, p.1-12.