TIMBER POLE INTEGRITY TESTING

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Statement

This is to certify that this thesis comprises:

- No material which has been accepted for the award to the candidate of any other degree, except where due reference is made in the text;

- Solely of my original work and due acknowledgement has been made wherever other previously published material and references are used; and

- Less than three words in length, exclusive of tables, maps, charts and bibliographical references.

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Baraneedaran (Bara) Sriskantharajah

February 2016
Abstract

Timber utility poles represent a significant component of Australia’s infrastructure. There are an estimated 5.3 million timber utility poles in Australia – with an estimated value of more than $12 billion (Rahman and Chattopadhyay, 2007). The nationwide annual demand for timber utility poles is increasing while the local supply of high quality poles is constrained (Lesley and Jack, 2006). Failure of poles can pose serious life safety and economic implications. There have been a number of reported incidents where poles failed while line workers were performing operations on the poles leading to fatalities (Nancy and Stout, 1998). It is also reported that failure of timber poles may have started some bush fires (Gary et al., 2010 Aug). Failure of poles can also lead to loss of power and possibly other supported services to large communities.

As timber poles deteriorate over time to varying levels, power distribution companies in Australia and overseas carry out routine inspections on such poles to assess their structural integrity. The common techniques used in Australia are visual inspection, sounding and drilling. These techniques are subjective methods and require highly skilled inspectors. Drilling practice is very common and it is a reasonable method for detecting damage at the location of drilling. However, it causes damage due to the holes left after the inspection. With frequent inspections, some poles may end up being condemned due to excessive number of drill holes. On the other hand sounding testing is non-destructive but it only detects near surface damage where tapping is applied and therefore the inspection area is limited by the reach of the inspector below and above ground. Hence, there is a growing demand by industry to develop more accurate and non-destructive methods for assessing the condition of poles in-service. These methods include stress wave propagation testing, experimental modal analysis and resistance drilling.

Several techniques that utilize Stress Wave Propagation (SWP) have been researched for use in non-destructive testing (NDT). SWP is widely used in the piling industry for evaluation of concrete piles. SWP velocity and reflections are affected by the properties of the medium the wave is traveling through and the presence of cracks or discontinuities.
Typically, the application of SWP testing in the piling industry is conducted in the longitudinal direction to the pile where the impulsive force (applied via hammer) is imparted on the top of the pile and the reflected stress waves are also measured at the top using a velocity meter. It is not practical to apply SWP in the longitudinal direction in timber poles as access to top of the pole is not practical. Therefore, for timber poles, the SWP technology needs to be adapted for application in the transverse direction to the poles. The application of SWP for in-service timber poles deals with transverse waves rather than the conventional compressional longitudinal waves used concrete piles. The aim of this thesis is to investigate the application of SWP testing for timber poles for detecting damage below and above ground.

This thesis presents an overview of design of timber poles and expected deterioration of poles while in service. It also provides review of the SWP testing and how it is normally used to detect damage. Based on preliminary finite element analysis and testing of timber poles, it was found that SWP testing could potentially be used for determining if poles have damage.

Accordingly a Beta Pole Tester was developed to collect more data from in-service timber poles. The SWP testing involves striking the timber utility pole with a hammer instrumented with a load cell and the pole response is measured close to the striking location with a geophone. The measured hummer impulse force and geophone velocity data are then analysed for key parameter including length of the pole and for any possible below or above ground defects.

Based on controlled timber pole tests and field trials, it was evident that the transverse SWP technique is a promising method for assessing the structural integrity of in-service timber poles. Further analysis was carried out using finite element (FE) models to find out the range of applicability and to identify the limitations of the transverse SWP technique for defect detection. The validated FE models showed that it is possible to identify below ground and above ground pole lengths and detect location of damage using the time record of the transverse SWP velocity.

This Beta Pole Tester was trialled in Christchurch New Zealand, and collected data from 600 in-service poles for quantitative analysis. Furthermore, specific healthy and
damaged poles where tested in Australia. The results from the hummer force and measured velocity response were critically analysed for all tested poles. These field results confirmed this testing technique can be used for damage detection. Using FE models, further parametric studies were carried out to investigate the effects of pole heights, diameter, tapering, defect severity, impulse location and impulse force magnitude. The results from these parametric study showed that this testing method is not sensitive to some common variables (such as pole length, diameter and tapering) and hence it can be a practical and robust method of assessment.
## Abbreviations

The following abbreviations are used throughout this thesis.

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>3D</td>
<td>Three dimensional</td>
</tr>
<tr>
<td>AS</td>
<td>Australian Standards</td>
</tr>
<tr>
<td>CCA</td>
<td>Copper Chromium Arsenate</td>
</tr>
<tr>
<td>CPU</td>
<td>Central Processing Unit</td>
</tr>
<tr>
<td>CSI</td>
<td>Centre for Sustainable Infrastructure</td>
</tr>
<tr>
<td>CWT</td>
<td>Continuous Wavelet Transformation</td>
</tr>
<tr>
<td>FEM</td>
<td>Finite element model</td>
</tr>
<tr>
<td>FE</td>
<td>Finite element</td>
</tr>
<tr>
<td>FFT</td>
<td>Fast Fourier Transform</td>
</tr>
<tr>
<td>HD</td>
<td>Hardwood</td>
</tr>
<tr>
<td>HT</td>
<td>Hilbert Transform</td>
</tr>
<tr>
<td>LT</td>
<td>Laplace Transform</td>
</tr>
<tr>
<td>MPG</td>
<td>Machine proof-grading</td>
</tr>
<tr>
<td>MSG</td>
<td>Machine stress-grading</td>
</tr>
<tr>
<td>NDT</td>
<td>Non-Destructive Testing</td>
</tr>
<tr>
<td>NZS</td>
<td>New Zealand Standards</td>
</tr>
<tr>
<td>SKM</td>
<td>Short Kernel Method</td>
</tr>
<tr>
<td>SW</td>
<td>Softwood</td>
</tr>
<tr>
<td>SWP</td>
<td>Stress wave propagation</td>
</tr>
<tr>
<td>VSG</td>
<td>Visual stress-grading</td>
</tr>
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My deep gratitude goes to Dennis Clancy and Powercor for their continuous support and enthusiasm towards the development of a non-destructive timber pole inspection technology. The research was made easier to complete because of Dennis by providing facilities to get the pole yard tests, in-service pole and relevant destructive testing of timber utility poles in the Powercor pole yard in Bendigo, Victoria. I gratefully acknowledge the knowledge and passion from Dennis Clancy towards maintaining the integrity of timber utility poles.

I owe special thanks to Orion Networks, Christchurch New Zealand for their contribution in facilitating the collection of transverse directional stress wave
propagation pole data. This information collected was very critical towards the research study, providing much needed data capture of many thousands of in service poles.

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Table of Contents

CHAPTER 1. INTRODUCTION AND SIGNIFICANCE .............................................. 1
  1.1 Introduction ................................................................................................. 1
  1.2 Research Aim and Objectives ..................................................................... 2
  1.3 Thesis Overview .......................................................................................... 3

CHAPTER 2. RESEARCH BACKGROUND .......................................................... 5
  2.1 Timber and Pole Property .......................................................................... 5
    2.1.1 Size and Form of Timber Poles ........................................................... 8
    2.1.2 Timber Sorting or Grading ................................................................. 10
    2.1.3 Durability Classes ............................................................................. 11
    2.1.4 Species Branding ............................................................................... 11
    2.1.5 Australian Timber Pole Resources ..................................................... 12
    2.1.6 Pole Standards and Specifications ..................................................... 14
    2.1.7 Design Considerations ....................................................................... 14
  2.2 Durability ...................................................................................................... 18
    2.2.1 Deterioration of Timber Poles ........................................................... 19
    2.2.2 Investigation and Identification of Factors for Deterioration ............ 21
    2.2.3 Detail Assessment of In-ground Decay ............................................. 22
    2.2.4 Termite Attack ................................................................................... 29
  2.3 Pole Identification ........................................................................................ 35
  2.4 Current Inspection and Assessment Techniques in Australia ..................... 36
    2.4.1 Above Ground Line Visual Inspection .............................................. 36
    2.4.2 Sounding Test .................................................................................... 37
    2.4.3 Drilling Inspection ............................................................................. 39
  2.5 Alternative Non-destructive Assessment Methods ...................................... 44
    2.5.1 Experimental Modal Analysis ............................................................ 44
    2.5.2 Stress Wave Technique ...................................................................... 52
    2.5.3 Resistance Drilling ............................................................................. 57
    2.5.4 Ultrasonic Waves ............................................................................... 59
  2.6 Discussion and Conclusions ......................................................................... 63
CHAPTER 3. INTRODUCTION TO STRESS WAVE PROPAGATION .................. 68

3.1 Stress Wave Propagation ................................................................. 68
3.2 Longitudinal Wave Propagation ...................................................... 69
3.3 Transverse Wave Propagation .......................................................... 73
3.4 Application of Transverse Waves to Timber Poles ......................... 73
3.5 Development of a Beta Pole Tester ................................................. 75
   3.5.1 Impulse Hammer ........................................................................ 77
   3.5.2 Geophone .................................................................................. 78
   3.5.3 Analogue to Digital & Data recorder .......................................... 78
   3.5.4 Toughbook Computer ............................................................... 79
3.6 Data collection and digital signal processing .................................... 81
   3.6.1 Fast Fourier Transform ............................................................. 83
   3.6.2 Short Kernel Method ................................................................ 84
   3.6.3 The Pole Tester Software Development ..................................... 87
3.7 Summary and Conclusion ............................................................... 90

CHAPTER 4. FE ANALYSIS AND FIELD TESTING OF TIMBER UTILITY POLES .... 91

4.1 Model Development ................................................................. 91
   4.1.1 Elements selection and description .................................... 92
4.2 Propagation of Longitudinal Waves ................................................ 93
   4.2.1 FE Analysis of a Concrete Pile .............................................. 94
   4.2.2 FE Analysis of Concrete Pile with Defect ............................ 98
   4.2.3 FE Analysis of an Intact Timber Pole ................................... 101
   4.2.4 FE Analysis of a Defective Timber Utility Pole .................... 106
4.3 Transverse FE Analysis ............................................................... 110
   4.3.1 Field Transverse SWP Inspection and Validating with FE Models .110
   4.3.2 Pole Yard Test and FE Analysis of an Intact Pole .................. 116
   4.3.3 Pole Yard Test and FE Analysis of Timber Pole with above ground
         Defect .......................................................................................... 123
   4.3.4 FE Analysis of Timber Pole with Above and Below Ground
         Defects ....................................................................................... 129
4.4 Field SWP Pole Testing and Confirming Results with Destructive
       Testing132
4.4.1 Investigation of Pole No 2 ............................................................... 132
4.4.2 Investigation of Pole No 18 ............................................................. 134
4.4.3 Detailed Investigation of Pole No 392 ............................................. 136
4.4.4 Detailed Investigation of Pole No 76 ............................................... 138
4.4.5 Detailed Investigation of Pole No 77 ............................................... 140
4.5 Stress Wave Propagation Summary and Conclusion ...................... 142

CHAPTER 5. FIELD TESTING AND HEALTH ASSESSMENT OF TIMBER UTILITY POLES 145
5.1 Introduction ......................................................................................... 145
5.2 Detailed Approach to Transverse SWP Velocity Trace Analysis. ............ 146
5.3 Christchurch Pole Testing and Results ............................................... 147
5.3.1 Effects of Pole Age, Height and Diameter with SWP Velocity...... 148
5.4 Health Assessment of Timber Utility Poles ........................................ 153
5.5 Field Testing Conclusion................................................................. 159

CHAPTER 6. PARAMETRIC STUDY OF TIMBER UTILITY POLES USING FE ANALYSIS 160
6.1 Height of Pole..................................................................................... 162
6.2 Diameter of Pole................................................................................ 163
6.3 Tapering Nature of Pole .................................................................. 164
6.4 Different Impulse Forces.................................................................... 165
6.5 Location of Impulse Force ................................................................ 166
6.6 Defect Severity ................................................................................. 168
6.7 Parametric Study Conclusion .......................................................... 170

CHAPTER 7. CONCLUSIONS AND FUTURE DEVELOPMENT ...................... 171
7.1 Summary and Conclusions .............................................................. 171
7.1.1 Research Background ................................................................. 171
7.1.2 Stress Wave Propagation ............................................................ 173
7.1.3 FE Analysis and Results ............................................................. 174
7.1.4 Field Testing and Health Assessment of Timber Utility Poles ....... 175
7.1.5 Parametric Study of Timber Utility Poles Using FE Models .......... 176
7.2 Recommendations for Future Research .......................................... 176
REFERENCES ...........................................................................................................................................178
APPENDICES .............................................................................................................................................182

Appendix A. Pole Design Loads and Load Combinations ...............................................................182
Appendix B. Sample Design of a Timber Pole ..............................................................................185
Appendix C. Main pole categories depending on treatment .....................................................191
   C1. Poles intended for use without full-length preservative treatment .....................191
   C2. Hardwood poles intended for use after full-length preservative treatment ..........192
   C3. Softwood poles intended for use after full-length preservative treatment ..........192
Appendix D. The Neutral Axis of a Pole .......................................................................................194
   D1 - In-line Pole without Service Mains ........................................................................194
   D2 - In-line Pole with Service Mains .............................................................................195
   D3 - Angle Pole ...........................................................................................................196
   D4 - Termination Pole .................................................................................................196
Appendix E. Sample Calculation for Decay of Timber Pole ......................................................197
   E1. Manual Calculation with Basic Empirical Equations .........................................197
   E2. Timber Service Life Tool Generated Results for Decay ....................................200
Appendix F. Strength Reduction with Drilling Inspection ...........................................................203
Appendix G. Pole Testing Software Development ....................................................................204
Appendix H. Christchurch Pole Data .........................................................................................215
Appendix I. Powercor Pole Data ..............................................................................................231
List of Tables

TABLE 2.1 – THE LIMITING PARAMETERS OF STRAIGHTNESS OF A TIMBER POLE ............................................ 9
TABLE 2.2 – RELATIVE STRENGTH OF STRUCTURAL GRADES ............................................................... 11
TABLE 2.3 – APPROXIMATE NATIVE HARDWOOD STATISTIC IN 2005 .................................................. 14
TABLE 2.4 – STANDARDS & SPECIFICATIONS FOR PRODUCTION & UTILISATION OF TIMBER POLES ...... 17
TABLE 2.5 – OPTIMUM PERFORMANCE OF PRESERVATIVE-TREATED POLES ........................................ 24
TABLE 2.6 – REPRESENTATIVE CLIMATE PARAMETER VALUES FOR THE HAZARD ZONES ..................... 26
TABLE 2.7 – EVALUATION OF HAZARD SCORE TOTAL ............................................................................ 34
TABLE 2.8 – THE POSITIONS OF THE NODES .......................................................................................... 48
TABLE 2.9 – EVALUATION OF MICRO DRILLING ...................................................................................... 58
TABLE 4.1– MATERIAL PROPERTIES USED IN THE ANALYSIS OF CONCRETE PILE .......................... 95
TABLE 4.2– MATERIAL PROPERTIES USED IN THE ANALYSIS OF TIMBER UTILITY POLE .................. 104
TABLE 4.3– ORTHOTROPIC MATERIAL PROPERTIES USED IN THE FE ANALYSIS FOR POLE 283 ....... 114
TABLE 4.4– ORTHOTROPIC MATERIAL PROPERTIES USED IN FE ANALYSIS ..................................... 120
TABLE 5.1– DETAILS OF SWP VELOCITY FOR DIFFERENT HEIGHTS, AGE AND HARD WOOD AND
SOFTWOOD POLES ................................................................................................................................. 149
TABLE 5.2– DETAILS OF SWP VELOCITY FOR DIFFERENT DIAMETER VS. AGE ................................. 151
TABLE 5.3– DETAILS OF SWP VELOCITY FOR DIFFERENT DIAMETER VS. HEIGHT ............................... 151
TABLE 6.1– MATERIAL PROPERTIES USED FOR PARAMETRIC STUDY OF EXAMPLE TIMBER POLE .... 161
TABLE F.1 – STRENGTH REDUCTION WITH THE NUMBER OF DRILLING INSPECTION HOLES .......... 203
List of Figures

FIGURE 2.1 : SECTION OF A TRUNK OF A TREE ................................................................. 6
FIGURE 2.2 : DETERMINATION OF STRAIGHTNESS ......................................................... 9
FIGURE 2.3: DETERIORATED TIMBER POLE BUTT ......................................................... 19
FIGURE 2.4: IDEALISED PROGRESS OF DECAY DEPTH WITH TIME .................................. 25
FIGURE 2.5: HAZARD MAP OF AUSTRALIA FOR TIMBER IN-GROUND DECAY ....................... 26
FIGURE 2.6: SCHEMATIC ILLUSTRATION OF RELATIVE DECAY RATES OF DIFFERENT TYPE WOOD .... 27
FIGURE 2.7: TIMBER LIFE OUTPUT RESULTS ..................................................................... 28
FIGURE 2.8: A POLE REMOVED FROM SERVICE DUE TO TERMITE ATTACK ............................ 29
FIGURE 2.9: TERMITE HAZARD MAP BASED ON TEMPERATURE ZONES .............................. 31
FIGURE 2.10: TERMITE HAZARD MAP BASED ON AGRO-ECOLOGICAL REGIONS OF AUSTRALIA ...... 32
FIGURE 2.11: SIMPLIFIED TERMITE HAZARD MAP ......................................................... 33
FIGURE 2.12: EFFECT OF DEPTH IN GROUND ON STABILITY ............................................ 37
FIGURE 2.13: ILLUSTRATION OF SOUND TESTING ............................................................ 38
FIGURE 2.14: DETAILS OF INSPECTION BELOW GROUND LINE .......................................... 40
FIGURE 2.15: INSPECTION HOLE SEALED WITH PLUGS ..................................................... 41
FIGURE 2.16: DISPLACEMENT OF A CANTILEVER BEAM .................................................... 46
FIGURE 2.17: FIRST FOUR FUNDAMENTAL MODES OF VIBRATION .................................... 48
FIGURE 2.18: THE DIFFERENT EMBEDDED CONDITION OF POLES TO THE GROUND .............. 50
FIGURE 2.19: VISCOELASTIC BAR OF LENGTH L SUBJECT TO AN IMPACT ............................. 52
FIGURE 2.20: THEORETICAL RESPONSE OF THE END OF A VISCOELASTIC BAR IN RESPONSE TO A PROPAGATING STRESS WAVE .......................................................... 53
FIGURE 2.21: THE PRINCIPAL MOVEMENT FOR THE PROPAGATION OF WAVES ....................... 60
FIGURE 2.22: A TYPICAL TIMBER UTILITY POLE REPLACEMENT IN PROGRESS ....................... 63
FIGURE 3.1: IMPACT OF ELASTICALLY CONNECTED SPHERES WITH NO END RESTRAINTS ................................. 70
FIGURE 3.2: IMPACT OF ELASTICALLY CONNECTED SPHERES WITH END RESTRAINTS ............... 71
FIGURE 3.3: THEORETICAL RESPONSE OF PILE HEAD (A) FREE ENDED CONDITION ..................... 72
FIGURE 3.4: STRESS WAVE RESPONSES; (A) INITIAL IMPACT; (B) PARTIAL REFLECTION AND PARTIAL TRANSMISSION AT CHANGE OF SECTION; (C) ARRIVAL OF REFLECTION FROM CHANGE OF SECTION TO THE SENSOR; AND (D) ARRIVAL OF REFLECTION FROM THE PILE TOE TO THE SENSOR (TURNER, 1997) ......................................................... 72
FIGURE 3.5: SCHEMATIC DIAGRAM OF STRIKING A POLE IN TRANSVERSE DIRECTION AND SWP PATTERN ................................................................................................................. 74
FIGURE 3.6: TYPICAL TRANSVERSE SWP VELOCITY TRACE OF A TIMBER UTILITY POLE .................. 75
FIGURE 3.7: BETA POLE TESTER ...................................................................................... 77
FIGURE 3.8: IMPULSE HAMMER ..................................................................................... 77
FIGURE 3.9: OMNI DIRECTIONAL GEOPHONE ................................................................. 78
FIGURE 3.10: DATA PHYSICS QUATTRO UNIT ............................................................. 79
FIGURE 3.11: SIGNALCALC CONTROL INTERFACE ................................................... 79
FIGURE 3.12: FIELD TOUGHBOOK COMPUTER .......................................................... 80
FIGURE 3.13: TYPICAL FIELD VELOCITY TRACE ....................................................... 82
FIGURE 3.14: TEMPORAL AND SPECTRAL IMPULSE FORCE INPUT DATA .................. 83
FIGURE 3.15: POLE VELOCITY TRACE AND APPLIED SKM KERNEL SEED .............. 86
FIGURE 3.16: COMPARISON OF FIELD (ORIGINAL) DATA AND SKM FILTERED DATA ... 87
FIGURE 3.17: INTERFACE: POST ANALYSIS OF TIMBER POLE TEST RESULTS .......... 88
FIGURE 3.18: TYPICAL OUTPUT FOR A TESTED POLE PROCESSED THROUGH MATLAB CODING .... 89
FIGURE 4.1: PILE GEOMETRY AND IDEALISED APPLIED IMPULSE FORCE ............... 95
FIGURE 4.2: POINTS RELATED TO THE SWP REFLECTION AS MEASURED AT THE TOP OF THE PILE .... 96
FIGURE 4.3: SWP TRACE OF AN INTACT CONCRETE PILE AS MEASURED AT TOP OF PILE ........ 97
FIGURE 4.4: GEOMETRY OF A CONCRETE PILE WITH A DEFECT AT 2.25M FROM THE TOP .......... 99
FIGURE 4.5: TRACE POINTS RELATED TO THE SWP REFLECTION AS MEASURED AT THE TOP OF THE PILE .................................................................................................................. 99
FIGURE 4.6: SWP TRACE OF A DEFECTIVE CONCRETE PILE AS MEASURED AT THE TOP OF THE PILE ... 100
FIGURE 4.7: COMPARISON OF VELOCITY TRACES AS MEASURED AT THE TOP OF AN INTACT AND DEFECTIVE PILE .................................................................................................................. 100
FIGURE 4.8: PRINCIPAL AXES OF WOOD WITH RESPECT TO GRAIN DIRECTION AND GROWTH RINGS 102
FIGURE 4.9: GEOMETRY AND THE IMPULSE APPLIED ON THE TIMBER POLE TESTED .......... 103
FIGURE 4.10: TRACE POINTS RELATED TO THE SWP REFLECTION MEASURED AT THE TOP OF AN INTACT POLE .................................................................................................................. 104
FIGURE 4.11: SWP VELOCITY TRACE OF AN INTACT TIMBER UTILITY POLE AS MEASURED AT THE TOP .................................................................................................................. 105
FIGURE 4.12: GEOMETRY AND THE DEFECT MODELL ED IN THE TIMBER POLE ANALYSIS ............. 107
FIGURE 4.13: TRACE POINTS RELATED TO THE SWP REFLECTION MEASURED AT THE TOP OF THE DEFECTIVE POLE .................................................................................................................. 107
FIGURE 4.14: SWP VELOCITY TRACE OF A DEFECTIVE TIMBER UTILITY POLE AS MEASURED AT THE TOP .................................................................................................................. 108
FIGURE 4.15: SWP VELOCITY TRACE COMPARISON OF INTACT AND DEFECTIVE TIMBER UTILITY POLE .................................................................................................................. 108
FIGURE 4.16: FIELD TESTED POLE 283 ........................................................................... 111
FIGURE 4.17: THE LENGTH AND APPLIED IDEALISED FORCE DETAILS FOR POLE 283 ............ 112
FIGURE 4.18: TRACE POINTS RELATED TO THE SWP VELOCITY REFLECTION MEASURED AT THE POINT OF IMPULSE .................................................................................................................. 112
FIGURE E.4: TIMBER LIFE RESULT-02 ................................................................. 202
FIGURE F.1: DIFFERENT DRILLING LOCATION AND ANGLE ...................... 203
Chapter 1. INTRODUCTION AND SIGNIFICANCE

1.1 Introduction

Timber as one of the oldest known building material is capable of transferring both tension and compression. It has a high strength to weight ratio which makes it relatively easy to fabricate and to join into reasonably sized members and structures. It often outperforms alternative materials in hazardous environments and extremes of environmental temperature. Furthermore, timber does not corrode and if detailed correctly, can be very durable. There are still several timber bridges that have remained in-service for more than 100 years in Australia and there are timber poles which has been in service for more than 50 years.

Failure of electricity distribution poles can have serious life safety and economical implications. There have been a number of reported incidents where poles failed when line workers were performing operations on the poles leading to fatalities. There are also reports suggestions that failure of timber poles has been responsible for igniting bushfires in Victoria and Western Australia. Failure of poles also leads to loss of power (and possibly other supported services) to large communities. Given that timber poles can deteriorate over time to varying levels, power distribution companies in Australia and overseas carry out routine inspections on their poles to assess their structural integrity. The most common techniques used in Australia are: visual inspection, sounding test and drilling. All these are subjective methods and require highly skilled inspectors to obtain reliable results. Drilling practice is very common and is a reasonable method for detecting local damage in the vicinity of where the drilling is performed. However, the drilling itself causes damage due to the holes left in the pole after each inspection. With frequent inspections, the pole may end up being condemned due to excessive holes within a small area of the pole.
Timber utility poles represent a significant component of Australia’s infrastructure. There are an estimated 5.3 million timber utility poles in Australia – with an estimated value of more than $12 billion (Rahman and Chattopadhyay, 2007). The nationwide demand for timber power poles was approximately 62,000 in 2004, 75,000 in 2006 and was estimated to be around 91,000 in 2009. On the other hand the maximum supply of poles was 62,300 in 2005 and 2006 and it was further noted that the ability to supply would remain the same from then on (Lesley and Jack, 2006). There are no more recent statistics found on pole resources such as nationwide annual pole requirements and supply level in Australia.

Given that it is critical to maintain healthy poles to prevent loss of life and services it is important to accurately access the integrity of existing poles to avoid their unnecessary replacement. Hence, there is a growing demand by industry to develop more accurate and reliable non-destructive methods for assessing the condition of in-service poles. This research is focused on investigating the development of such a method specifically for timber utility poles.

1.2 Research Aim and Objectives

The overall aim of this research is to develop an in-service assessment tool for timber utility poles using a non-destructive testing technique. There are a number of objectives with appropriate methodologies associated with these needed to achieve the overall aim of the research. These objectives and associated methodologies are summarised below.

1. Undertake a literature review to identify current practice in Australia in terms of selection and durability of timber poles. Details such as size, durability class and species branding will be discussed. In addition the standards relating to timber poles will be reviewed to understanding the design and maintenance procedures. Further, the identification of different factors affecting the durability of poles mainly decay and termite activity will be analysed. Finally, the current pole inspection techniques will be critically reviewed.

2. Review the fundamentals of the stress wave propagation (SWP) technique for damage detection and its potential application for timber poles. The successful application of SWP in the piling industry will give insight of the technology and its merits to apply the technology for use with timber utility poles.
3. Carry out preliminary tests on poles and perform finite element analysis to confirm the suitability of SWP for damage detection in timber poles. Perform preliminary field application of SWP and investigate the experimental results against finite element analysis.

4. Undertake detailed study of SWP on poles with different damage to validate a developed time domain methodology for damage detection in timber poles.

5. Apply SWP technique for a large number of poles to examine the different physical properties of poles in SWP results. This will help to set parameters based on collected SWP velocity, impulse force and duration.

6. Carry out parametric study using calibrated FE models to demonstrate effectiveness of SWP as a non-destructive damage detection tool. The parametric study will cover pole height, diameter, tapering nature of poles, different impulse forces and defect severity.

1.3 Thesis Overview

The critical literature review covering the project background is presented in Chapter 2. The Chapter reviews in depth; timber properties and relevant Australian Standards, timber durability, deterioration, detail assessment of in ground timber deterioration and termite attack, current inspection system, alternative non-destructive inspection techniques and previous research on non-destructive inspection of timber utility poles.

In Chapter 3, an extensive review of the SWP technology for the non-destructive inspection of timber poles is presented along with the development of a Beta pole tester. The SWP principle in longitudinal and transverse directions are described with illustrations and examples. Details of the application of the Beta pole tester in the field are also covered. The chapter ends with the review of the collected field data and development of a pole testing software.

Chapter 4 covers the FE analysis and field application of the Beta pole tester. A finite element model is used to simulation the SWP in concrete piles and timber utility poles using ANSYS computer package. The longitudinal directional SWP is verified for concrete piles while the transverse directional SWP for utility poles were verified against
calibrated data. These models were used to detect various types of defects below and above ground of the timber utility pole. Further field trials with the Beta pole tester is conducted on timber utility poles and verified the results by removing the poles and dissecting at particular locations identified by the SWP inspection. Details of five poles tested with the Beta pole tester using SWP technology for Powercor are presented the end of the chapter.

In Chapter 5, the large scale trialing of Beta Pole Tester and quantitative analysis of parameters such as input impulse force, force duration, different pole species, height, diameter and age are discussed in detail. Further, the field health assessment of poles based on the impulse force parameters is presented in this chapter. Furthermore, this chapter discusses in detail FE parametric study covering the effects of pole height, pole diameter, tapering nature of the pole different impulse force, impulse force location and defect severity.

Finally, significant conclusions and benefits from the research are presented in Chapter 7 together with recommendations for further research.
Chapter 2. RESEARCH BACKGROUND

2.1 Timber and Pole Property

Botanically commercial timbers fall into two main groups, namely softwoods and hardwoods. The former are gymnosperms, commonly referred to as conifers of cone-bearing plants, characteristically with needle or awl-shaped leaves and naked seeds. The latter represent one group of the angiosperms known as the dicotyledons which characteristically have broad leaves and seed enclosed to a higher state than the gymnosperms with a larger number of cell types each having a specific function. Although the division into softwood and hardwood is convenient for differentiating two broad groups of timber there are a few timbers, for example pitch pine, among the softwoods that are actually harder than some hardwoods (e.g. balsa, lime and willow). Further, the divisions are not always applied correctly, particularly in the tropics. For example, native softwoods in such regions are usually soft hardwoods as they are broad leaved species with soft wood, although they are frequently referred to as softwoods (Desch and Dinwoodie, 1996).

Although there are many species that produce woody stems, only a small proportion of these actually grow to timber size. Even so, the number of species producing commercial timber runs into several hundreds. The characters available for distinguishing timber are not numerous, and structural identification is based on an examination of features that are known to be reliable rather than on the more obvious characters such as colour and weight, which tend to be far from consistent. Figure 2.1 describes a typical section of a tree.
Figure 2.1: Section of a trunk of a tree

Source: NSW Department of Industries, Forest web page.

Usually the bulk of the cross-section of a tree is the heartwood. Around the heartwood, in a broad ring, lies the sapwood. It is paler in colour compared to the heartwood and is often whitish or cream coloured. Heartwood consists of dead material. It helps support the tree and has no role in the growth of the tree. Sapwood, on the other hand, is made up of living cells that carry water and nutrients upwards from the roots. It is this water and nutrient mixture that makes up a tree's sap.

Heartwood appears to provide only structural support for the plant. Its cells become blocked with deposits that contribute considerably to the colour of the wood and are mainly responsible for the enhanced durability of heartwood (Bootle, 2004). At the time of heartwood formation, balloon-shaped intrusion called ‘typoses’ extend from parenchyma into the vessels of heartwoods and sometimes into the resin canals of pines. They can also contribute to the clogging of the tissue. The combination of deposits and tyloses make heartwood difficult to penetrate with preservatives. Closing of the pits between some cells at heartwood formation also adds to the difficulty of penetration.

The amount of sapwood present on a tree stem is a genetic characteristic of a species and varies from a narrow band of perhaps 10mm to instances where the whole cross-section of a tree is sapwood (Bootle, 2004). There are numerous theories which attempt to explain why sapwood is converted to heartwood but it seems clear that as a tree gets bigger there is usually no need for the whole cross-section to be involved in the conduction of sap and
the storing of food reserves. A balance is reached. The redundant sapwood is converted into physiologically inert heartwood and the valuable minerals previously held in these cells are used to promote the production of more wood. Thus, the tree makes full use of the minerals within reach of its root system. There can be a transition zone between sapwood and heartwood in some species (e.g. spotted gum) but usually there is a sharp line of demarcation indicated by a distinctive change in the colour of the wood, provided that it is not a pale-coloured species.

The great difference between the durability of the sapwood and heartwood of many species is essentially due to the concentration of toxic compounds of phenolic type in the heartwood (Bootle, 2004). This give rise to higher durability with heartwood compared to sapwood. The presence of high concentration of resins in some softwood, although not of much inherent toxicity, can be of some value in promoting durability because they restrict the uptake of moisture.

Availability of species, in the sizes that may be needed, usually varies in response to local and international prices and demand for products. Depending upon the locality, the following species are available on a reasonably sustainable basis in Australia, though the sizes and grades available may be limited.

Softwoods;

- Australian pine (seasoned and locally produced), radiata, pinaster, slash, Caribbean pines
- Radiata pine (seasoned or unseasoned and imported)

Hardwoods;

- Unseasoned hardwoods, mixed species such as blackbutt, spotted gum, flooded gum, tallowwood, stringy bark (Qld, NSW); karri (WA) messmate and ash-type eucalypts (Vic, Tas, SA)
- Seasoned hardwoods (mixed species) blackbutt (Qld, NSW), jarrah (WA)
- Seasoned mountain ash (most readily available in Vic, Tas and NSW, but also available elsewhere)
2.1.1 Size and Form of Timber Poles

Australian Standard 2209-1994 (Timber poles for overhead lines) defines the dimensions such as length, girth and diameter for unseasoned poles i.e. poles measured within 14 days of cutting or re-wetting by Copper Chromium Arsenate (CCA, waterborne) preservative treatment. Due allowances are made for shrinkage where poles are re-measured after this interval.

The size tolerance such as length, ground line diameter or girth and other dimensions specified by the purchaser are to be within the nominated tolerances. A plane normal to the axis of the pole usually located at a distance of 600mm plus 10% of the nominal length from the butt end is the nominal ground line. The critical zone of the pole is within 1m above nominal ground line and 0.6m below the nominal ground line (i.e. 1.6m length in total). This is the region where pole deterioration or damage is most common. An additional zone measured from the top of the pole equivalent to the length between the nominal ground line and the butt of the pole is included in the critical zone when the pole is nominated as a stayed pole. The diameter of a pole which is not preservative treated is designated as the diameter of the heartwood, since the untreated sapwood is not durable and is therefore neglected in the calculation of the strength of untreated poles.

Diameter measurements for the purpose of determining compliance with dimensional requirements are usually derived from the circumference at the point nominated. When ovality is considered, the least diameter of a pole is required not to be less than 80% of the greatest diameter at any section over a maximum 80% of the length of the pole.

When measured in accordance with Figure 2.2, the maximum deviations of sweeps, crooks or kinks are not to exceed the values for X as given in Table 2.1 for straightness of a timber pole.

The butt and top are generally cut square to the axis of the pole and all bark is removed. The size of a knot is generally measured as the distance between two lines parallel to the longitudinal axis of the pole and enclosing the knot or cluster of knots. The diameter of an encased knot is measured to the sound wood of the pole on either side of the knot.
Figure 2.2: Determination of Straightness

Source: AS 2209-1994; Timber-Poles for overhead lines

Table 2.1 – The limiting parameters of Straightness of a timber pole.

<table>
<thead>
<tr>
<th>Type of Deviation</th>
<th>Measured Length m</th>
<th>Max. deviation, X, mm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Select Grade</td>
<td>Standard Grade</td>
</tr>
<tr>
<td>(A) Single sweep and Multiple sweep where pole outline is not crossed by line pq</td>
<td>L</td>
<td>7L</td>
</tr>
<tr>
<td>(B) Multiple sweep where pole outline is crossed by line pq₁</td>
<td>L</td>
<td>5L</td>
</tr>
<tr>
<td>(C) Crooks and kinks</td>
<td>L/4</td>
<td>3L</td>
</tr>
<tr>
<td>(D) Butt sweep</td>
<td>2</td>
<td>if D* ≤ 400mm = 1.5D</td>
</tr>
<tr>
<td></td>
<td></td>
<td>if D* &gt; 400mm = 1.25D</td>
</tr>
</tbody>
</table>

* Where D = actual pole diameter 2m from butt

Source: AS 2209-1994; Timber-Poles for overhead lines
Finally, splits and barrel checks in poles are assessed by comparison with a numerical rating provided in AS2209 of Figures 1.2 and 1.3. Further, these illustrations, which can be only used as a guide, are typical of free-splitting species. Mechanical constraints for the control of end splits are permitted.

2.1.2 Timber Sorting or Grading

Grading is the process by which the timber is sorted into groups with ideally, similar structural properties in each group. There is a substantial range of properties within a group and significant overlap in properties between groups. Structural grading can be performed in a number of ways including the following:

- Visual stress-grading (VSG)
- Machine stress-grading (MSG)
- Machine proof-grading (MPG)

The two most commonly used methods in Australia are visual stress-grading and machine stress-grading. In theory, any method that sorts timber into groups of material with similar structural properties could be used. However, in order to be valid, the sorting method must produce results which are both consistent and repeatable. To achieve this level of reliability, “rules” for using accepted sorting methods have been developed. In most countries, including Australia, these “rules” are generally either industry standards or national standards. The relevant Australian Standards are the following:

- AS 2878: Timber – classification into strength groups.
- AS 3519: Timber – Machine Proof Grading

In the process of Visual stress-grading, a qualified person examines each length of timber that has been produced at a mill. This visual inspection is undertaken in accordance with two visual grading standards AS 2082 and AS 2858, which define strict rules as to the type sizes and positions of physical characteristics that are allowed into each “group” or Structural Grade of material. The grader is required to examine each timber specimen on
all surfaces before it is placed in a stack corresponding to Structural Grade 1 (highest structural properties) through to Structural Grade 5. The relationship between clear wood and the various structural grades is shown in Table 2.2.

<table>
<thead>
<tr>
<th>Structural Grade</th>
<th>% of clear wood strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>No 1</td>
<td>75%</td>
</tr>
<tr>
<td>No 2</td>
<td>60%</td>
</tr>
<tr>
<td>No 3</td>
<td>48%</td>
</tr>
<tr>
<td>No 4</td>
<td>38%</td>
</tr>
<tr>
<td>No 5</td>
<td>30%</td>
</tr>
</tbody>
</table>

*Source: Timber design Handbook (Geoffrey and Crews, 1998)*

2.1.3 Durability Classes

The service performance of any timber pole in weather exposed situations or high moisture environments depends on how well it is protected from absorbing moisture. High moisture content in timber poles promotes timber degradation while timber poles kept dry does not decay. Timber poles are chosen from different durability classes and treated separately for different environmental hazard levels. Timber poles are usually classed into four groups based on their service life in various conditions. Class 1 & 2 are the most durable while classes 3 & 4 have less service life.

2.1.4 Species Branding

Timber poles are branded legibly on the butt end with code letter(s) as soon as practicable after felling to indicate the species of the timber pole. These are provided in AS2209: Timber-Poles for overhead lines Appendix B.
2.1.5 Australian Timber Pole Resources

A review by the Energy Networks Australia in October 2006 revealed that about 68,100 durability Class 1 & 2 poles were required in 2005 (Lesley and Jack, 2006). However, only about 62,300 durability Class 1 & 2 poles were available from both public and private resources during 2005. This was considered the maximum annual amount of the traditional resources that will ever be available. The demand for new durability Class 1 & 2 poles in 2006 was predicted to be 74,900 poles, while the supply of traditional native forest-grown hardwood poles was estimated to remain at about 62,300 poles.

Under current native forest management policies, the estimated total sustainable log availability is expected to fall by 36% from Australia’s public forest between 2001 and 2039, and by 25% from private forests (Nolan et al., 2005). The amount of higher durability pole timber that will be available from public native forests is generally fixed at various quantities throughout the country until 2039. It was reported however, that significant volumes of lower durability hardwood logs are likely to be available from native forests in New South Wales for pole production in the immediate future and some poles may be available from public forests in Victoria.

According to NSW Department of Primary Industries – Forests, approximately 40,400 durability Class 1 and 2 hardwoods are currently harvested from NSW public forests annually for pole production, along with 2,610 durability Class 3 hardwoods (Lesley and Jack, 2006). These quantities represent both native and plantation-grown logs which are supplied to pole customers according to agreements established with NSW Department of Primary Industries – Forests that generally apply until 2023. The current demand for the traditional pole resource is beginning to exceed the available supply, especially for 11, 12.5 and 14m long poles.

According to Queensland Department of Primary Industries – Forestry and Queensland pole producers approximately 60% of the native hardwood pole resource was traditionally sourced from public forests and about 40% obtained from private forests (Lesley and Jack, 2006). Department of Primary Industries – Forestry reports that approximately 19,800 Class 1 and Class 2 timber poles are currently available from Queensland public forest each year. The most commonly supplied pole lengths are 11 and 12.5m, and the
Volume supply in year 2006 is considered close to the maximum available. 14m poles are in limited supply and longer poles are rare.

About 80% of the poles produced in Tasmania are harvested from public forests and 20% are obtained from private forests (Lesley and Jack, 2006). According to Forestry Tasmania, approximately 5,800 durability Class 3 and 4 poles per annum are sold from Tasmanian State Forests. This volume obtained from public forests is considered the maximum available and is sold exclusively in Tasmania. Most of the timber poles from public forests are re-grown, however native forest management policies may impact the availability of the timber poles over the next few decades.

Unfortunately in Victoria no significant volumes of native forest-grown durability Class 1 or 2 species suitable for pole production are available from the public or private forests (Lesley and Jack, 2006). A reasonable volume of lower durability species may potentially be available for pole production in the future.

Native hardwood supply in Western Australia has been rapidly diminishing for several years, especially since 2001, when heavy restrictions were placed on harvesting from south west forests. Preservative-treated plantation-grown P-radiata has been the main source of timber distribution poles over the past two years, and over that time about 13,500 poles have been used. Only about 30% of new poles in Western Australia are hardwoods sourced from Western Australian native forests.

No significant quantities of native durability Class 1 or 2 hardwood timber poles are available from public or private forests in South Australia, Australian Capital Territory and Northern Territory public or private forests, nor are likely to be in the future. A summary of approximate native hardwood pole supply from public and private forests in 2005 is shown in Table 2.3. One implication of lack of supply of suitable poles is that existing poles should be properly assessed while in service to avoid unnecessary premature replacement.
Table 2.3 – Approximate native hardwood statistic in 2005

<table>
<thead>
<tr>
<th>State/Territory</th>
<th>Durability Class</th>
<th>Approximate Number of poles</th>
</tr>
</thead>
<tbody>
<tr>
<td>New South Wales</td>
<td>1 &amp; 2</td>
<td>40,400</td>
</tr>
<tr>
<td></td>
<td>3 &amp; 4</td>
<td>2,610</td>
</tr>
<tr>
<td>Queensland</td>
<td>1 &amp; 2</td>
<td>19,800</td>
</tr>
<tr>
<td>Western Australia</td>
<td>1 &amp; 2</td>
<td>2,100</td>
</tr>
<tr>
<td>Tasmania</td>
<td>3 &amp; 4</td>
<td>8700</td>
</tr>
</tbody>
</table>

Source: Energy Networks Australia, October 2006.

2.1.6 Pole Standards and Specifications

Most energy providers in Australia classify timber poles according to their length and strength. Pole lengths are measured in 1.5 metre increments ranging from about 8 m to 24.5 m. The ‘tip load’ system is most commonly used to calculate pole strength classifications. The ultimate ‘tip load’ assigned to a pole represents the maximum force in kilo-Newton (kN), applied at a pole’s top (tip), above which the pole may not maintain its structural integrity. There are some differences in standard tip loads between States, and many energy providers’ specifications use tip loads that are calculated based on working stress principles and timber properties assigned using the strength group / stress grade system in Australian Standard AS 1720.1 (1997). A number of other Standards also apply to the production and utilisation of timber poles. Energy providers may have their own internal specifications based on the national or industry standards, with additional specific requirements for poles used in the locations of their networks. A summary of the common documents for design and specifications of timber poles is shown in Table 2.4.

2.1.7 Design Considerations

The Australian Standards AS 2209-1194 (Timber – Poles for overhead lines) & AS/NZS 4676:2000 (Structural design requirements of utility services poles) are the two main standards used for specification and design Timber Poles for overhead lines. All the timber utility poles should be designed and checked for stability, strength, serviceability, durability and vehicle impact. Each and every timber pole intended for service should
pass the pole requirements detailed in AS 2209-1194: Timber – Poles for overhead lines before they are transported to pole yards. The factors considered in choosing utility pole are the size tolerances such as length and groundline diameter (girth), ovality, straightness, knots, checks for end splits and barrel checks as discussed earlier.

Timber poles can be used for various purposes such as street lighting, flood lighting, aerial conductor, traffic signal, communication and multi usage poles. These are called the usage classes of utility service poles. Further, these poles are categorized into three importance classes. They are;

- **Class I**
  Poles supporting vital post-disaster services or collapse of the poles and loss of the supported services would cause unacceptable danger to life or extensive economic loss

- **Class II**
  Collapse of poles would cause negligible danger to life and property and alternative arrangements can be provided if loss of the supported services occurs

- **Class III**
  Where collapse of the poles or loss of the supported services is more tolerable with respect to social and economic consequences than the above classes I and II.

The importance classes prioritize the consequences of failure or collapse of timber utility poles while they in-service. The designer can make adjustments to design parameters of timber utility poles based on the importance class.

Currently, timber utility poles are generally used after application of full length preservative treatment. Different types of treatments and their requirements are detailed in AS1143 (High temperature creosote for the preservation of timber) and AS 1604 (Timber-preservative treated-sawn and round).

Generally, design of timber poles includes loads such as dead loads, snow and ice loads wherever applicable, wind loads, earthquake loads, live loads and maintenance loads and aerial cable loads. The design action effects of bending moment, shear, torsion, deflection and rotation need to be addressed carefully during the design of a utility pole. Much
attention is paid for embedment depth, instability due to overturning, rotation and if applicable settlement design of timber poles.

Appendix A lists the loads and load combination to be considered in a timber utility pole design and Appendix B provides a detailed design example for a timber utility pole showing considerations for all relevant loads and strength requirements.
<table>
<thead>
<tr>
<th>Standard Documents</th>
<th>Title and description</th>
</tr>
</thead>
</table>
| AS 1720.1 – 1997    | *Timber Structures Part 1: Design methods*  
Provides designers and manufacturers of timber structures with limit-state design methods, design data, and testing procedures for different types of structures.                                                                                                                                               |
| AS 1720.2 – 1990    | *SAA Timber Structures Code Part 2: Timber properties*  
Provides tables of common timber species’ properties that can be used for design of timber structures.                                                                                                                                                                                         |
| ESAA C(b)1 – 2003   | *Guidelines for design and maintenance of overhead distribution and transmission lines*  
Provides the basic principles for the design of overhead lines with a focus on reliability-based design.                                                                                                                                                                                               |
| AS/NZS 4676:2000    | *Structural design requirements for utility services poles*  
Provides fundamental design requirements for pole structures supporting: street or floodlighting, road or railway signalling equipment, aerial conductors carrying electric power or communication signals, and equipment for communication through the atmosphere.                                                                                           |
| AS 2209 – 1994      | *Timber – Poles for overhead lines*  
Provide required specifications for hardwood and softwood timber poles with or without full length preservative treatment.                                                                                                                                                                           |
| AS 2878 – 2000      | *Timber - Classification into strength groups*  
Specifies the unseasoned and seasoned strength group of most of the timber species used in Australia. Establishes procedure to classify timber species into strength groups.                                                                                                                                                                   |
| AS 1604.1 – 2005    | *Specification for Preservative Treatment. Part 1: Sawn and Round Timber*  
AS 1604 series of wood preservation standards provide specifications for preservative penetration, retention. The complementary AS 1605 series of standards provide analytical methods for monitoring treatment quality.                                                                                     |
| AS 5604 – 2005      | *Timber - Natural Durability Ratings*  
Provides natural durability ratings (expected service-life) for a number of Australian and imported timber species for a range of biological hazards.                                                                                                                                                           |
2.2 Durability

With time and the influence of the environment, most materials exhibit a loss in performance, a process which is generally known as degradation. In timber, undesirable changes occur and the material loses its mechanical performance specially strength and toughness. The rate of the degradation is usually specific to a particular species and to specific environmental conditions. Some timber species show good resistance to degrading while others have little resistance.

Durability can be defined as the capacity of a product, component, system, building or structure to perform the function for which it was designed, be it aesthetic, structural or amenity for a specified period of time. Durability considerations are important in ensuring an appropriate life for the structure being designed. The designer has an expectation of performance of timber for a given number of years, usually the service life of the pole. The performance could be compromised by several factors.

If timber is protected from weathering and mechanical damage, a sound heartwood timber can last virtually indefinitely, as evidences by the articles thousands of years old that have been removed from the pyramids in Egypt or by the bloodwood log removed in 1940 from the mud 14m below the waterline in Sydney Harbour in an ‘as new’ state after an estimated 20,000 years of burial (Bootle, 2004).

In terms of durability, timber poles can be divided into three main categories as below:

- Poles intended for use without full-length preservative treatment
- Hardwood poles intended for use after full-length preservative treatment

These categories are discussed in detail in Appendix C.

Australian Standard AS 2209-1994 (Timber - Poles for overhead lines) provides normative reference information describing timber species that can be used to support overhead lines. Eighteen durability Class 1 species and 22 durability Class 2 species are described. Only these species can be used without full-length preservative treatment, unless otherwise agreed between the purchaser and supplier. If a pole’s sapwood remains untreated, however it must be assumed that any untreated sapwood does not contribute to
the strength of a pole. The Standard prescribes that if any of the durability Class 1 and 2 species are intended for use after full-length preservative treatment, then preservative penetration is required to the full depth of any sapwood present, with an additional requirement that the depth of the sapwood must be no less than 12 mm. In the case that a pole is confirmed to be a durability Class 1 species by a recognised authority, the minimum sapwood depth requirement does not apply.

2.2.1 Deterioration of Timber Poles

Timber is an organic material and therefore it is not surprising to find that it is subjected to attack by a whole host of biological agencies. Because of the significance of biological degradation to the performance of timber in service and because of the variable and sometimes complex nature of the degradation it is important understand this form of attack. *Figure 2.3* shows a typical deteriorated below groundline core which is usually not visible from the surface.

*Figure 2.3: Deteriorated timber pole butt.*

Most forms of decay in timber are caused by fungi that feed either on the wall tissue or cell contents of woody plants. The very fine spores of these fungi are abundant in the air and under favourable conditions of temperature and dampness and in the presence of
oxygen they will attack timber especially if it contains easily digested sugars and starches which are commonly present in sapwood. On the other hand, heartwood is less readily attacked because it contains very few readily digestible nutrients for fungi and also the present of toxic extractives which varies greatly between species. Timber that is at moisture content below a certain level or that is saturated with water to the point where oxygen is in restricted supply to the fungi, is not subjected to fungal attack (Bootle, 2004).

There are exceptions of course and the group of fungi called “soft rot” and some bacteria can thrive in the low oxygen conditions in saturated timber and attack the wood cells. Soft rot and bacterial attack can develop at an accelerated rate in cooling towers and also near the ground line of poles especially in fertilised fields in hot climates.

**Dry rot and Wet rot**

Dry rot and wet rot are often loosely used in reference to timber decay but they are better avoided as they tend to give an erroneous impression of the process involved (Bootle, 2004). As mentioned earlier, timber must have a moisture content of above 20% before there is a serious risk of decay but this could scarcely be described as ‘dry’ under Australian conditions. The only true ‘dry rot’ is that caused by *Serpula lacrimans* (also called *Merulius lacrimans*) which is most common in Europe but sometimes found in Victoria and which has the ability of conveying the necessary life-supporting moisture from adjacent areas onto dry timber and infecting it. Its presence is indicated by a dust of red spores. Fortunately it has made relatively little headway in Australia.

It is important to distinguish between wood rotting fungi responsible for decay in timber, and those that feed on the cell contents. Wood-rotting fungi seriously weaken timber, ultimately rendering it valueless whereas sap-stain fungi spoil the appearance of timber but do not affect most strength properties. Some fungi attack primarily the heartwood of standing trees while others chiefly colonise and decay logs after felling or sawn timber during the process of seasoning.
Conditions for fungal attack

Timber will not be subjected to fungal attack unless the following four unfavourable conditions are satisfied; (Mackenzie et al., 2007).

- The correct moisture is present.
  
  0-20% Moisture Content – attack will not occur – too dry
  20-60% Moisture Content – sufficient moisture for attack to occur
  >60% Moisture Content – too wet with insufficient oxygen for attack to occur

- Oxygen is available. Timber completely submerged or saturated timber is rarely attacked and timber 600mm or more below ground is rarely attacked due to lack of available oxygen.

- Temperature is in the range of 5-40°C (25-40°C is ideal). At lower temperatures, fungal attack is retarded. At higher temperatures, the fungus will not survive.

- Food in the form of nutrients e.g. carbohydrates, nitrogen and minerals is present. These are usually provided by the timber itself, particularly sapwood which is normally high in sugar and carbohydrates.

Removal of any one of these four conditions will prevent fungal attack, although in practice, it is usually the removal of moisture that requires the greatest consideration.

Consequently timber is best protected from fungal action by:

- Eliminating contact with moisture or

- Where this is not possible, by using species with durability appropriate to the application or by using species that have been preservative treated to a level appropriate to the hazard.

2.2.2 Investigation and Identification of Factors for Deterioration

High moisture content in the soil increases the probability of biological attack. It is significant when the moisture content is more than 20%. In clayey soils, the moisture and chemicals are trapped inside the soil and cause algae, moss, and mould to grow which
attack the timber poles, thereby causing faster deterioration. On the other hand, by virtue of their permeability, cohesion-less sandy soils allow drainage and reduce moisture content. Fibre saturation occurs when moisture content reaches around 30% (Rahman and Chattopadhyay, 2007).

The mass of a unit volume of soil (i.e. bulk density) is generally expressed in g/cm$^3$. The volume includes both solids and pores. Thus, soils that are light and porous will have low bulk densities, while heavy or compact soils will have high bulk densities. Presence of excessive acidity or alkalinity of groundwater in soils can be quantified by the pH value of the ground water. Presence of chloride, sulphate, carbonates or magnesium salts in soil are the indication of salinity. High salinity can cause decay of the timber. A build-up of salts can also be a threat to the foundation.

Seasonal changes also influence cyclic stresses on the pole. Climate has influence on soil condition and properties since the moisture content and temperature of soils changes with climate.

Poles in the Australia and most other countries are treated nowadays with preservatives to provide a protective shell against fungi and insects. However, this protection diminishes over time, permitting degradation of the outer surface, typically by the action of the soft rot, and also degradation of the internal cells. According to Australian Standard AS 2209-1994, hardwood poles are preferred in Australia because of their natural strength. In Australia, 14 different eucalypts have been used. The Australian Standard allows durability Class 1 and 2 species to be used for utility poles that are not full length preservative treated.

### 2.2.3 Detail Assessment of In-ground Decay

In-ground decay is a major problem with timber poles widely used in electricity and telecommunication industry. Soil factors influential to in-ground decay were identified after analysis of failure data from electricity supply industries (Wang et al., 2008). Based on the above a detailed in-ground decay study was conducted by Baraneedaran et. al (2009). Higher failure rate was observed in areas with clayey soils. Sampling of soils from the identified areas and subsequent analysis increased the understanding of decaying process of the in-ground portion of timber poles. Testing methods for identification of
influential soil factors were developed. The moisture content, pH value (acidity/alkalinity), bulk density, salinity and electrical conductivity are the factors influence on in-ground decay of timber pole. It is also found that the chemical composition of soil such as presence of Kaolin or Quartz has some influence on the decaying process. This is due to the fact that Kaolin allows more water to be trapped inside the soil. This causes algae, moss and mould to grow and attack the in-ground portion of timber poles. Findings resulted in recommendation of different installation specifications to improve drainage system in clayey soil areas. Other methods for corrective measures include soil compaction and liming of soil where needed. Findings from this investigation can be useful in deciding inspection intervals, maintenance actions and replacement decisions of timber poles, bridge footings, house stumps and railway sleepers.

Responsible design will take these factors into account and specify:

- Appropriate timber species.
- Appropriate chemical treatment to give performance over the required lifetime.
- Sizes that allow for satisfactory performance after some loss of section; and
- Detailing that will minimise the factors that lead to degradation.

A summary of recommendations to ensure the optimum performance of preservative treated poles are given in Table 2.5.

Mallet & Grgurinovic (1996) explain that fungi are the primary recyclers of organic matter in forest ecosystems, and these organisms are best able to decompose timber and use it as an energy source. In the context of timber decay, both reproductive and vegetative fungal structures may be observed. Fruiting bodies like brackets contain copious microscopic spores, which are eventually released into air currents or spread by rain droplets. When these spores fall on timber that contains sufficient moisture, they germinate and produce fine threads (or hyphae) which can penetrate the timber. Vegetative filamentous hyphae may be recognised growing through a piece of decaying timber.
Table 2.5 – Optimum performance of preservative-treated poles

<table>
<thead>
<tr>
<th>Procedure</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Improved pole treatment</td>
<td>Season all poles properly before treatment</td>
</tr>
<tr>
<td></td>
<td>Pre-bore and cut all poles</td>
</tr>
<tr>
<td></td>
<td>Incise or through bore/radial drill or kerf cut refractory species</td>
</tr>
<tr>
<td></td>
<td>Undertake post treatment analysis and inspection to assure quality</td>
</tr>
<tr>
<td>Best management practice</td>
<td>Limit preservative retention to that prescribed in standards</td>
</tr>
<tr>
<td></td>
<td>Reduce surface deposits on poles</td>
</tr>
<tr>
<td></td>
<td>Limit potential for bleeding of preservatives (important for creosote)</td>
</tr>
<tr>
<td></td>
<td>Allow time for adequate fixation of waterborne preservatives</td>
</tr>
<tr>
<td>Cradle to grave management</td>
<td>Good initial specification</td>
</tr>
<tr>
<td></td>
<td>Quality control inspections</td>
</tr>
<tr>
<td></td>
<td>Careful installation</td>
</tr>
<tr>
<td></td>
<td>Regular inspection program maintained (Inspection logs and records)</td>
</tr>
<tr>
<td></td>
<td>Pole reinforcement when required</td>
</tr>
</tbody>
</table>

Based on a comprehensive study of timber degradation, Wang et. al (2008) produced empirical models which predict timber decay in ground. The decay rate is a function of parameters related to both wood and climate. When the decay rate is calculated according the empirical models developed by the researchers, designers are able to predict the expected service life of a timber pole.

A basic assumption for the decay model is that progress of decay depth with time (t) in a timber element follows an idealised bilinear relationship characterised by a decay lag, \( t_{lag} \) (years), and a decay rate, \( r \) (mm/year). A schematic illustration of this relationship is shown in Figure 2.4. Thus for given \( d_0 \) which is the initial decay depth which affects the
The strength of a timber utility pole, $t_{lag}$, and $r$, the decay depth after $t$ years of installation, $d_t$ (mm), is expressed as follows:

\[
d_t = \begin{cases} 
ct^2 & \text{if } t \leq t_{d_0} \\
(t - t_{lag})r & \text{if } t > t_{d_0}
\end{cases}
\]

(2.1)

\[
c = \frac{d_0}{t_{d_0}^2}
\]

(2.2)

\[
t_{d_0} = t_{lag} + \frac{d_0}{r}
\]

(2.3)

The value of $d_0$ in equation 2.3 can be determined by experimental evidence or expert opinion. If none is available, $d_0 = 5$ mm is recommended. The decay lag and decay rate are correlated; therefore, for given decay rate $r$, the decay lag $t_{lag}$ (years) is determined by:

\[
t_{lag} = 5.5r^{-0.95}
\]

(2.4)

![Figure 2.4: Idealised progress of decay depth with time](image)

Decay rate, $r$ for untreated timber is assumed to be the product of multipliers that take into account the effects of material and climate as follows:

\[
r_{untreated, \text{timber}} = k_{\text{climate}} \times k_{\text{wood}}
\]

(2.5)

Where; $k_{\text{climate}}$ – climate parameter

$k_{\text{wood}}$ – wood parameter
The climate parameter $k_{\text{climate}}$ is used to produce an in-ground decay hazard map for Australia that delineates the continent of Australia according to the relative vulnerability of locations to fungal decay due to the climatic variation. A hazard map that divides the continent into four hazard zones is shown in Figure 2.5. Zone D is the most hazardous region and Zone A is the least hazardous.

![Hazard map of Australia for timber in-ground decay](image)

*Figure 2.5: Hazard map of Australia for timber in-ground decay*

*Source: Wang et. al. (2008)*

Values for $k_{\text{climate}}$ for the four zones and the boundaries between the four zones shown in Figure 2.5 are listed in Table 2.6.

*Table 2.6 – Representative climate parameter values for the hazard zones*

<table>
<thead>
<tr>
<th>In-ground decay hazard zone</th>
<th>Representative area $k_{\text{climate}}$</th>
<th>Boundary area $k_{\text{climate}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.5</td>
<td>1.0</td>
</tr>
<tr>
<td>B</td>
<td>1.5</td>
<td>2.0</td>
</tr>
<tr>
<td>C</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>D</td>
<td>3.0</td>
<td></td>
</tr>
</tbody>
</table>
The values of wood parameter are available separately for heartwood with respect to durability Classes and sapwood. The heartwood is divided into inner heartwood (core wood) and outer heartwood as shown in Figure 2.6. Further, Figure 2.6 shows the relative decay rates of inner, outer, treated and untreated sapwoods. The $k_{\text{wood}}$ values are as follows;

$$
k_{\text{wood,heart}} = \begin{cases} 
0.23 & \text{class } -1 \\
0.48 & \text{class } -2 \\
0.76 & \text{class } -3 \\
1.36 & \text{class } -4 
\end{cases}
$$

$$
k_{\text{wood,sap}} = \begin{cases} 
2.72 \text{ for heartwood} \\
5.44 \text{ for softwood} 
\end{cases}
$$

$$
k_{\text{wood,core}} = 2k_{\text{wood,heart}}
$$

Figure 2.6: Schematic illustration of relative decay rates of different type wood

Source: (Wang et al., 2008)

The climate parameter ($k_{\text{climate}}$) depends on mean annual temperature and rainfall. When a treated timber utility pole is considered, modification factors are applied for the decay rate $r$ for different types of treatment system such as CCA. Equation 2.6 presents the modified decay rate for treated timber.

$$
r_{\text{treated,sap}} = \frac{r_{\text{untreated,sap}}}{1 + B \times C_{\text{CCA-equiv}}}
$$

(2.6)
Chapter 2

Research Background

\[ B = \begin{cases} 
45 & \text{softwood} \\
12 & \text{hardwood} 
\end{cases} \]

The decay can occur inward from the peripheral and outward from the core of a timber pole. The models developed by the researches cover both inward and outward decay for timber with sapwood and de-sapped. The decay rate \( r \) changes with each inward and outward direction. With the above method, we can predict the decay rate for timber utility poles depending on time and climate factor all around Australia. A sample design calculation for a typical pole decay located in the Melbourne is covered in Appendix E.

Appendix B provides a detailed design example for a timber utility pole. The fungal decay calculation in Appendix E is based on the parameters taken in Appendix B. The fungal decay was calculated from empirical model equations and then verified with the “Timber Life” tool generated results. The properties of the timber pole subjected to the above calculations are 300mm diameter, 14m height, desapped, untreated and red ironbark pole. According to the calculations from empirical model equations, the decay depth would be 16.8mm in 25 years. The “Timber life” tool gives results as shown in Figure 2.7.

![Figure 2.7: Timber life output results](image)

It was found that external decay would be around 15mm for the duration of 25 years and there would be no internal decay within the period. These results help the designer in selecting the design parameters of timber poles incorporating the loss of cross section with time.
2.2.4 Termite Attack

Termites are the cause of the greatest economic losses of timber in-service in Australia and are a significant factor in the degradation of trees growing in forest areas (Bootle, 2004). However, most termite species are grass feeders or feed on decayed timber in or on the ground and are important converters of fallen trees to organic matter and minerals. Some of these non-pest termite species occur in the same areas as the pest species and it is therefore professionally important to be able to distinguish them and discuss treatment or non-treatment options with building owners. Since termites can remain concealed in the wood for years, it is often not easy to realise possible termite activity, until termite damage is extensive. Figure 2.8 shows a timber pole damaged due to termite attack. It was found that, termites invaded up through the core part of the pole up to 1m above the ground level without being visible from outside.

![Figure 2.8: A pole removed from service due to termite attack](image)

Durability against termite attack is measured differently to durability against decay, and timber species are characterised as either susceptible or not susceptible to termite attack (Australian Standard AS-5604, 2005). If a species is susceptible to attack by termites, the rate of attack depends on the size, age and vigour of the attacking termite population. According to Peters and Fitzgerald (2007), termites may broadly be categorized as being either subterranean, damp wood or dry wood. Subterranean termites are generally ground-dwelling or require contact with some constant source of moisture. Most termites that damage timber-in-service in Australia are subterranean. These termites seek dark humid
positions for a nest, such as in an old stump or the damp, poorly ventilated foundations of a building. Damp wood termites generally live in damp rotting logs or in dead or living trees. They may be found in decaying timber in-service, but generally they are of little economic concern. Dry wood termites obtain water from the wood in which they feed and have no contact with the soil, or with any other source of moisture. These termites are of economic concern, but are mostly confined to the coastal and adjacent tableland areas of tropical and sub-tropical Australia. These are mostly found in damp tropical climates such as coastal of Queensland where the high equilibrium moisture content of the timber itself provides a satisfactory level of moisture (Creffield, 2005).

Most of the studies conducted to estimate the probability of attack by termites are on houses. These studies could provide some understanding and knowledge of the probability of attack by termites on timber poles.

A detailed analysis by Leicester et. al. (2008b) has been made on termite tally data in houses to provide information in terms of probability of attack. In order to perform this, the houses were grouped in terms of specified set parameters. Then for each group, the probability of a termite incidence is approximated by noting the proportion of that group that has been attacked in the past. These probabilities are then related to other parameters that are averaged for the group. The following three types of groupings or zones were considered:

- Temperature zones
- Agro-ecological zones
- Housing clusters (this does not relate the attack possibility by termites on timber utility poles).
Analysis of termite tally based on temperature zonation

Australia is divided into three zones based on temperature for termite activity as follows:

- Zone 1: $T_{\text{mean}} < 18^\circ \text{C}$
- Zone 2: $18^\circ \text{C} \leq T_{\text{mean}} < 25^\circ \text{C}$
- Zone 3: $T_{\text{mean}} \geq 25^\circ \text{C}$

$T_{\text{mean}}$ denotes the mean annual temperature. A hazard map based on temperature is shown in Figure 2.9. The hazard increases with increase of the temperature, hence zone 3 represents the highest termite hazard. The incidence of termites in Tasmania is taken to be zero.

![Figure 2.9: Termite hazard map based on temperature zones](image)

Source: Leicester et. al. (2008b)

For research performed on houses, the probability of termite attack on a house is more strongly correlated with the age of the house than with any other parameter. It could be argued that the same could apply for timber poles.
Analysis of termite tally data based on Agro-Ecological zonation.

The agro-ecological zonation of termite hazard was developed by Cookson & Trajstman (2002) and is based on agro-ecological regions of Australia as defined by the Commonwealth of Australia (1991). A detailed procedure for the prediction of termite attack or incidents is described by Leicester et. al. (2008b).

As part of the ‘design for durability’ research program, a map of termite incidence was developed by Cookson & Trajstman (2002) as shown in Figure 2.10. Further a simplified developments of termite hazard models were presented by Leicester and Wang (2003), and four termite hazard zones were identified for Australia (Figure 2.11). The relative decay hazard that is present throughout Australia for timber used in contact with the ground, ranges from least severe in Zone A to most severe in Zone D.

![Termite hazard map based on agro-ecological regions of Australia](image)

*Figure 2.10: Termite hazard map based on agro-ecological regions of Australia*  
*(Cookson and Trajstman, 2002)*
The model makes a quantified risk estimate on each specific house based on a number of parameters related to that house. The input parameters chosen for practical application are as follows:

- Termite hazard zone
- Age of surrounding suburbs
- Distance of house from boundary
- Wood in the garden and under the house
- Type of ground contact for the house
- Environment of vulnerable timber

However, for practical application some approximations are introduced. First, each hazard parameter is given a hazard score, depending on whether it is considered to describe a high, medium or low hazard (Leicester et al., 2008a). These hazard scores are denoted by a number $h$. They have been derived from empirical models. Then for each particular house, the hazard scores are added so as to obtain a hazard score total, denoted by $H$. The factors are listed in Table 2.7 with the respective index and values. The scores for each $h_1 - h_7$ are calculated and added to find out the hazard score total $H$. The zone classification for hazard $h_1$ is shown in Figure 2.11. Zone A is not taken into account.
From Zone B to D the scores are given 0, 2 and 4 respectively for $h_1$. Once the hazard score has been evaluated for each of the parameters $h_1$ – $h_7$, the hazard score total $H$ is obtained as a summation of these scores as indicated in Table 2.7.

**Table 2.7 – Evaluation of hazard score total**

<table>
<thead>
<tr>
<th>Hazard Factor</th>
<th>Index</th>
<th>Hazard Parameter</th>
<th>Hazard Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location zone</td>
<td>$h_1$</td>
<td>B, C, D</td>
<td>0, 2, 4</td>
</tr>
<tr>
<td>Age of suburb</td>
<td>$h_2$</td>
<td>&lt;10 Yrs, 10-70 Yrs, &gt;70 Yrs</td>
<td>0, 2, 4</td>
</tr>
<tr>
<td>Distance to boundary</td>
<td>$h_3$</td>
<td>&gt;8 m, 2-8 m, &gt;8m</td>
<td>0, 0.5, 1.0</td>
</tr>
<tr>
<td>Wood in garden</td>
<td>$h_4$</td>
<td>Low, medium, high</td>
<td>0, 0.5, 1.0</td>
</tr>
<tr>
<td>Ground contact</td>
<td>$h_5$</td>
<td>Low, medium, high</td>
<td>0, 1, 2</td>
</tr>
<tr>
<td>Construction material</td>
<td>$h_6$</td>
<td>Low, medium, high</td>
<td>0, 1, 2</td>
</tr>
<tr>
<td>Timber exposure</td>
<td>$h_7$</td>
<td>Low, medium, high</td>
<td>0, 1, 2</td>
</tr>
<tr>
<td>Hazard Score Total (H)</td>
<td></td>
<td></td>
<td>0-16</td>
</tr>
</tbody>
</table>

In addition to the above parameters, there are two more supplementary hazard parameters. They are the inspection (I) and maintenance (M) parameters. The parameter I is calculated with the period between inspections and the parameter M by the period between chemical treatments.

For engineering purposes, it is useful for a given termite attack to be a probabilistic event. The study by Leicester and Wang (2008) describes the development of a model to predict the risk of attack on a house in Australia. The model is developed to evaluate the attack probability of termites on houses with parameters such as location zone ($h_1$), age of suburb ($h_2$), distance to the boundary ($h_3$) and wood in garden ($h_4$). Unfortunately, most of the parameters are not related to evaluate the attack probability of termite on timber poles. Some of the parameters should be omitted and revised to suit with timber poles. The probability of termite attack is predicted mainly based on the Total Hazard Score (H) value. The H is a numerical summation of hazard factors from $h_1$ to $h_7$ as shown in Table 2.7. The probability of termite attack will end up with erroneous information if the same model is adopted with timber poles.
Most of the studies conducted to estimate the probability of attack by termites are on houses. These studies provide basic understanding and knowledge of probability of termite attack. There is merely no studies made on termite attack of timber pole. Further, the above study helps to get an idea of how each factors weight with the termite attack prediction, the region where termite activities are high and how termite attack can be minimised.

2.3 Pole Identification

Inspection of timber poles ensures the structural stability of the poles throughout their design life. Periodical inspections of poles generally cover issues related to loss of ground support, vertical alignment and deterioration. For effective asset management (including inspection, maintenance and replacement) each pole must have a unique identification. In Australian practice, each pole is identified by an identification plate (Pole disc) which contains the most important pole information as discussed below.

The pole disc gives the full details such as the height of the pole, strength group, species, year of purchase, hazardous classification, etc. Unfortunately in Australia, the pole discs varied over time and incorporated additional information such as timber treatment type, hazard type, treated year which is needed for inspection of the poles. Generally the pole identification disc is located at one of two positions on the timber pole. Discs installed prior to 1997 are fitted 2m from the nominal ground line only in Newcastle and Hunter areas in NSW whereas in other places they were at 4m from the butt. After 1997 in all the places, discs have been fitted 4m from the butt.

Poles purchased from 1974 to 1982 were fitted with an aluminium identification disc recessed into the timber 4m from the butt. The discs were 40mm in diameter and included information are length, year of purchase, timber species and strength classification of pole. Pole disc purchased from 1982 to 1988 had the same information as before but were arranged in a different way to the earlier discs. Poles purchased after 1988 is still the current practice but there are three different options with pole discs. These new identification discs are 50mm in diameter to enable more information to be recorded. Details can be found in Pole inspection & treatment procedures (Energy Australia, 2006).
2.4 Current Inspection and Assessment Techniques in Australia

In Australia, a typical pole inspection procedure generally consists of the following major actions;

- Above ground line visual inspection.
- Sounding.
- Drilling.

The above ground visual inspection generally includes features such as variation of depth in ground by inspecting the ground level changes and, vertical alignment as described in Section 2.4.1. Sounding and drilling are used to examine the quality of wood and assess extent of deterioration due to fungal decay or termite infection as described in Sections 2.4.2 and 2.4.3.

In partial excavation inspection and assessment, extreme caution is exercised when excavating around a pole as most of them are loaded with active distribution cables and other items such as transformers. This assessment focuses on of the below ground section of the pole, with inspection of the location between the ground line and 350 mm below this line as shown in Figure 2.13. This section of the pole is commonly referred to as the critical zone because it is subject to the most bending load and generally suffers the greatest degradation due to the relative moisture and oxygen levels in this layer of soil (Energy Australia, 2006).

2.4.1 Above Ground Line Visual Inspection

Failure to place a pole deep enough in the ground can severely reduce the stability of the pole. Also, it is important to be aware if the ground level is lowered relative to the pole, the pole may lose significant stability with any reduction of depth in ground. Figure 2.12 illustrates the significance of ground lines on pole stability. Typically, road re-alignment work may result in a pole having less depth in ground. Evidence on the pole of an old ‘ground level’ mark, or ‘high tide’ mark indicates that the pole is no longer as deep in the ground as originally installed. The pole disc gives the exact length of the pole, which is a good indicator to find the depth in ground of the pole. Great care is required before digging out a pole that has less depth in ground than when originally installed.
Vertical alignment

It is required to look for reasons why a pole is leaning and the consequences of the lean such as reduced conductor clearance or traffic obstruction caused by pole leaning into a traffic lane or driveway. Poles with leaning angles more than 10° are noted in the inspection report. The angle of the pole is accurately measured rather than estimated.

2.4.2 Sounding Test

Sounding testing of timber utility poles is carried out with a hammer by striking the pole as far as it can be reached below the ground line, then a rounded point bar (usually a 5 mm radius point) is used to test the pole from the bottom of the excavation up to the ground line (Figure 2.13). The bar usually serves a dual purpose with a chisel point at one end and a rounded point on the other end. The chisel-end is used to scrape soil and decayed timber away from the pole. A bar weighing 6 kg with a ‘rounded point’ ground hemispherically to a 10 mm diameter (or 5 mm radius point) has been found to be ideal for inspection of most timber utility poles (Energy Australia, 2006).
The pole is struck firmly at the base of the excavation so the bar strikes the pole where it meets the soil. The bar will deflect off the pole if the pole is solid at the base of the excavation. After testing at the base of the excavation, the bar is used to impact the pole immediately above the point, then tested again every 50 mm in a vertical line up to the ground line. The pole is tested in this manner at least every 100 mm around the pole.

Particular attention is paid to the area of the pole at and below the bottom of the excavation. Generally, there will be detectable decay near the bottom of the excavation when severe decay exists deep below the excavated area. In most instances the pole’s condition will improve with depth, however under some conditions the pole will deteriorate below the excavated area. If the external decay increases below the excavated area, the investigation is extended by digging to 400 mm from 350mm, but not beyond as this may destabilise the pole. The problem is reported to the relevant authorities if it
extends below 400 mm. A pole with a significant defect below the bottom of the excavation may also be loose in the ground, and special care is taken and an alert is issued for any movement of the pole in-ground when struck with a bar at the base of the excavation.

By testing a pole in the manner described, the point of the bar should penetrate decayed timber to reveal the true extent of the remaining sound timber. The maximum depth that the point of the rounded point bar penetrates into decayed timber is the depth that the measuring callipers are placed in order to measure the reduced diameter below the ground line. Also, where the pole sounds hollow, the bar is driven vigorously into the suspect area. This will result in either the bar penetrating a thin wall of sound timber or bouncing off if adequate sound timber exists.

This method of testing identifies timber degradation on the external surface of the pole, and internal defects close to the surface of the pole. This method does require significant experience by the inspector to ensure confidence of the results. Similar to drilling this method requires some subjective judgement, however it is not destructive.

### 2.4.3 Drilling Inspection

New timber poles are generally not internally inspected by drilling during the first five years from the date of their installation or when Copper Chrome Arsenate (CCA) is pressure impregnated. Even, under the following circumstances, poles may still require internal inspection;

- The timber species is Blackbutt,
- There is evidence of active termites in the pole,
- There is evidence of fungal decay,
- Sounding test indicates a defect in the pole,
- In any instance on CCA poles over 15 years old, where the CCA treated timber below ground line is defective,
- A possible defect is indicated during the visual inspection process,
- There is no pole disc observed.

45° angle drilling is normally used to assess the pole between the ground line and 350mm below ground as shown in Figure 2.14. Mostly these kinds of drilling may be
accompanied by excavation around the pole. In such cases, caution is exercised as poles are loaded with active distribution cables and other items such as transformers.

All below ground inspection holes are drilled at 45° to the pole (Figure 2.14). Inaccurate drilling angles will generate inaccurate sound wood measurements. It is necessary to be accurate to within plus or minus five degrees to obtain an acceptable result. All above ground inspection holes are drilled at approximately 90° to the pole face except the inspection holes for reinforced poles. These inspection holes are angled upwards at approximately 5° so water will drain out. All inspection holes drilled are generally sealed with blue plugs (usually 30mm long see Figure 2.15) (Energy Australia, 2006). However, above ground inspection holes for reinforced poles are sealed with grey plugs to identify their purpose.

If a pole is severely degraded, full excavation around the pole is not performed. It is immediately assigned for replacement. On the other hand, excavation is carried out for only sufficient material to allow an internal inspection to be carried along the neutral axis 100 mm below the ground line (see Appendix D details of neutral axis). It is usually excavated to a depth of 350mm to visually inspect the condition of the pole below 100mm from ground line. This will give a better correlation to the 45° drilling inspection results at 100mm below ground. When the pole has become degraded and the inspector considers the pole being loaded close to or beyond its available capacity, or it appears to be in danger of immediate collapse, excavation is not continued and the pole is reported for
replacement. When it is considered safe to proceed, full excavation around the pole to a
depth of 350 mm is done. Inspection for any termite activity in the excavation and the
excavated soil is carried out. The pole is scraped with a chisel pointed bar to remove loose
soil and debris, as well as any decayed timber. Using a rounded point bar, the pole is
tested for the soundness of the exposed timber. The testing for the soundness of a timber
utility pole is discussed in Section 2.4.2.

![Inspection hole sealed with plugs](source: www.preschem.com)

The objective of drilling is to examine if internal damage is present and if so assess the
size and cause of the defect to determine the remaining sound timber. This assessment is
carried out by drilling into the timber in the area to be assessed in such a manner that the
drill will indicate to the inspector whether it is penetrating sound timber or not. Internal
inspection is carried out using a 14 mm auger bit. It is never suggested to use a larger size
bit as this size has been found to produce consistent results while keeping the hole as
small as possible (Energy Australia, 2006). The sound the drill makes, the smell of the
wood shavings, the feel of the drill, the resistance to its progress and how strongly the
worm on the drill pulls into the timber will all provide indications about the condition of
the timber. It is imperative that the drill not be pushed through the timber.
The inspector would drill carefully until the first sign of an internal defect is detected. Then a gauge is inserted into the bored hole until it rests against the end of the hole and the depth of the drill is recorded. After recording the depth of drill, the probe is removed and drilling continued. When the drilling starts again and the wood is still sound, then the first reading is disregarded and continued. However, when the renewed drilling confirms the start of the defect, the recorded measurement gives the front wall thickness. The drilling will continue to the back wall of the defect and the measurement of the defect is recorded. The drilling activity is continued until the inspector feels that the far side of the defect is reached and may have encountered sound wood. At this moment, drilling is stopped and with the probe another measurement is recorded. Once again the probe is removed and it is confirmed that the measurement is taken to the far side of the defect accurately by continuing to drill another 20 mm. Based on these readings, the wall thickness is then calculated.

It is usual practice that all poles have a minimum average wall thickness of 70 mm anywhere at or below the ground line (Energy Australia, 2006). When the average of the wall measurements obtained from internal inspections is less than 70 mm at or below the ground line, the pole is classified as defective.

Crews and Yeates (2000) noted that an ideal method of pole assessment would be able to indicate a pole’s remaining strength, serviceability classification and remaining life with a level of reliability commensurate with that of the rest of the network. Prior to the mid-1980s however, if inspection was done at all, the procedure was usually minimal excavation followed by superficial examination and sounding with an axe or hammer. Suspected poles were only sometimes drilled to examine their internal condition. Based on anecdotal reports and industry experience, Crews and Yeates (2000) showed that these inspection methods did not keep the failure rate below acceptable levels and that premature pole condemnation was excessive.

Crews and Yeates (2000) further explained that over the previous decade or more, network managers developed improved asset management systems, which involve routine inspection of most poles. It is noted that the modern “section modulus” inspection method is based on the assumption that the remaining strength is proportional to the modulus of the cross-section of the sound wood in the critical plane. The section modulus
method involves drilling inspection holes into the pole in the ground-line region, estimating the depth of any decay voids and examining the condition of timber shavings extracted during drilling. Any loss of cross-section is then calculated, and the section-modulus (Z) is calculated by subtracting the area of decayed timber from the theoretical sound wood area based on the pole diameter. The bending capacity of the pole is then calculated as the product of the section modulus and the timber species’ standard strength (usually 80 to 100 MPa for traditional hardwood poles). The strength of the pole is assumed to be adequate not only at the time of the test, but until its next inspection, if it is 100% or more than the assumed design load. It should also be noted that drilling holes in poles is destructive to the pole and will ultimately make the pole unserviceable if too many holes are drilled. (A sample calculation of strength reduction due to drilling inspection is presented in Appendix G)

While drilling along the neutral axis which has minimal effects on strength, inadequately-treated inspection-holes may promote deterioration. Another limitation of the section modulus method is that a reasonable degree of subjectivity is involved, associated with the position of drill holes and assumptions on the internal extent of decay. Furthermore, it is also difficult to detect early decay, when a significant loss of strength may have occurred without noticeable change in the appearance of timber-shavings. Finally, given the discrete location of the drilling, it is quite possible to miss decay completely if it is below or above the position of drill holes.
2.5 Alternative Non-destructive Assessment Methods

Given the limitations of sounding which only detects surface and near surface damage and the destructive and subjective nature of drilling, other testing methods have been explored for assessing in service timber poles. These methods are non-destructive and include:

- Experimental modal analysis
- Stress wave testing
- Resistance drilling
- Ultrasonic waves

It should be noted that non-destructive testing techniques for timber differ greatly from those for homogeneous, isotropic materials such as metals, plastics, and ceramics. In such non-timber-based materials, whose mechanical properties are known and tightly controlled by manufacturing processes, NDT techniques are used only to detect the presence of discontinuities, voids, or inclusions. However, in timber, these irregularities occur naturally and may be further induced by environmental deterioration. Therefore, NDT techniques for timber need to consider both environmentally induced irregularities and how these affect its mechanical properties.

The following section briefly describes the above mentioned techniques which could be used to evaluate timber poles.

### 2.5.1 Experimental Modal Analysis

There has been extensive research done on the use of change of dynamic parameters for damage detection of structures. Changes in structural properties lead to change in dynamic modal parameters such as natural frequencies, mode shapes and modal damping values. These parameters can be obtained from dynamic (vibration) testing (Avitabile, 2001).

The most useful damage detection methods are probably those using changes in resonant frequencies because frequency measurements can be quickly conducted and are often quite reliable (Salawu, 1997). Abnormal loss of stiffness is inferred when measured
natural frequencies are substantially lower than expected or compared to signature values in a pole as new condition.

Samali et al. (2014) carried out the research in development and implementation of vibration-based methods for evaluation of damage and state of health of timber structures. They developed a modified damage index method (MDI) for dealing with timber beam-like structures, and a damage index method for plate-like structures (DI-P) was proposed for timber bridges and timber decks to detect damage and damage severity estimation. These both methods were formulated based on modal strain energy.

In order to obtain the dynamic properties of a structure (a timber pole in this case) using experimental modal analysis, the structure needs to be excited with sufficient energy to evaluate as many modes as possible. Further, there should be sufficient locations of measurement along the structure to be able to detect the mode shapes and their frequencies. These two issues represent a significant limitation for application of experimental modal analysis for damage detection in timber poles. This is due to the fact an inspector can only access up to 2m of the height of the pole without the use of mechanical aids and hence the density of measurement along the height of a pole would be poor.

Further, impact excitation using a modal hammer is only possible within the same 2m off the ground. Hence, there may not be adequate energy to excite a sufficient number of vibration modes.

This method is explained further using an example. A timber utility pole can be idealized to a cantilever beam. The theory of vibration of a cantilever beam (Bendat and Piersol, 1980), after making a number of simplifying assumptions, leads to the following equation of motion for the displacement at x for beam shown in Figure 2.16:

\[
\frac{\partial^4 Y(x, t)}{\partial x^4} = -\left(\frac{\rho A}{E I}\right) \frac{\partial^2 Y(x, t)}{\partial t^2}
\]

(2.7)

Where:

- \(A\) Cross-sectional area of the beam [m²]
- \(\rho\) Mass density of the material [kg m⁻³]
E  Young’s modulus for the material [kg m⁻¹ s⁻²]
I  Second moment of area of the cross-section

\[ Y(x,t) = Y(x) e^{j\omega t} \]

Substitution in Equation (2.7) now gives for the amplitude function \( Y(x) \)
\[
\frac{\partial^4 Y(x)}{\partial x^4} = \left( \frac{\omega^2 \rho A}{EI} \right) Y(x) \tag{2.8}
\]

We can see by inspection that the sine and cosine functions will solve this equation since their 4th derivatives reproduce themselves. The hyperbolic sine and cosine functions also have this property. So one way to write the most general solution is
\[
Y(x) = A \cos(\lambda x) + B \sin(\lambda x) + C \cosh(\lambda x) + D \sinh(\lambda x) \tag{2.9}
\]

The value of \( \lambda \), which satisfies the boundary conditions, has to be found. This form of \( Y(x) \) gives
\[
\frac{\partial^4 Y(x)}{\partial x^4} = \lambda^4 Y(x) \tag{2.10}
\]

Comparing Equations 2.8 and 2.10 we see that \( \lambda \) and \( \omega \) are related by
\[
\lambda^4 = \frac{\rho A \omega^2}{EI} \quad \text{or} \quad \omega = \lambda^2 \sqrt{\frac{EI}{\rho A}} \tag{2.11}
\]
Each possible value of \( \lambda \) gives a ‘mode’ and Equation 2.11 gives the associated frequency of the mode.

For later convenience we will replace \( \lambda \) with the substitution \( \lambda = \frac{\theta}{\ell} \), so

\[
\omega = \frac{\theta^2}{\ell^2} \sqrt{\frac{EI}{pA}} = \frac{\theta^2}{\ell^2} \sqrt{\frac{EI}{pA\ell^4}}
\]

(2.12)

where \( \ell \) is the total length of the cantilever beam

It remains to discover what values of \( \theta \) are appropriate to the cantilever problem, and what the shape of the beam looks like for each \( \theta \).

Equation 2.7 and its solution 2.9 are generally applicable to vibrating beams. The constants in 2.9 and the value of \( \lambda \) (or \( \theta \)) appropriate to a particular case are determined by the relevant boundary conditions that the solution must satisfy.

In the case of the cantilever, the boundary conditions are

\[
Y(0) = 0; \quad \frac{dY}{dx}\bigg|_{x=0} = 0; \quad \frac{d^2Y}{dx^2}\bigg|_{x=\ell} = 0; \quad \frac{d^3Y}{dx^3}\bigg|_{x=\ell} = 0
\]

The application of these conditions leads to solutions for \( Y(x) \) of the form

\[
Y_n(x) = \cosh\left(\theta_n \frac{x}{\ell}\right) - \cos\left(\theta_n \frac{x}{\ell}\right) - \sigma_n \left[ \sinh\left(\theta_n \frac{x}{\ell}\right) - \sin\left(\theta_n \frac{x}{\ell}\right) \right]
\]

in which the \( \theta_n \) are the solutions of \( \cosh(\theta_n) \cos(\theta_n) = -1 \)

Consider a timber utility pole having a height of 10m above ground level idealised to a cantilever beam. Figure 2.17 shows the first four fundamental modes of vibrations. There is no nodal point present for the first mode of vibration. The second mode of vibration will have a nodal point at approximately \( \frac{3}{4} \) of the total height of the pole. Assuming 2.0m from the ground is the maximum reachable height by a person to place accelerometers for modal analysis Table 2.8 shows that the minimum height will be 3.59m for the first nodal point from the bottom of the pole in fourth mode of vibration. It is practically not
possible to place accelerometers at the top of a pole to get all of its modes of vibration. Hence, observing modal shapes will not be possible but it may be useful to monitor the natural frequencies of each mode of vibration. The angular frequencies, $\omega_n$ of every mode can be driven by Equation 2.13.

$$\omega_n = 2\pi F_n = \theta_n^2 \sqrt{\frac{EI}{\rho Al^4}}$$

(2.13)

$\theta_n$ is a number that is given in Table 2.8 for the first four modes of vibration.

![Figure 2.17: First four fundamental modes of vibration](image)

**Table 2.8 – The positions of the nodes**

<table>
<thead>
<tr>
<th>n</th>
<th>x/l</th>
<th>x/l</th>
<th>x/l</th>
<th>$\theta_n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.87510</td>
</tr>
<tr>
<td>2</td>
<td>0.784</td>
<td>-</td>
<td>-</td>
<td>4.69409</td>
</tr>
<tr>
<td>3</td>
<td>0.504</td>
<td>0.868</td>
<td>-</td>
<td>7.85476</td>
</tr>
<tr>
<td>4</td>
<td>0.359</td>
<td>0.644</td>
<td>0.905</td>
<td>10.9955</td>
</tr>
</tbody>
</table>

The presence of damage or deterioration causes changes in the natural frequencies. The change in natural frequency is a relatively easier damage detection parameter to determine the changes in the model shapes. It is possible to obtain first, second, third and fourth natural frequencies of a timber pole from Equation 2.13 to compare with experimentally acquired natural frequencies.

Consider the same parameters taken for the design of the timber pole in Appendix B.
CHAPTER 2

RESEARCH BACKGROUND

<table>
<thead>
<tr>
<th>Property</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red ironbark pole</td>
<td>Hardwood, Durability Class 1</td>
</tr>
<tr>
<td>Cross sectional Area</td>
<td>Circular in shape</td>
</tr>
<tr>
<td>Mean Diameter</td>
<td>300mm</td>
</tr>
<tr>
<td>Height of the pole</td>
<td>10m (above ground)</td>
</tr>
<tr>
<td>Preservation</td>
<td>Desapped, untreated.</td>
</tr>
<tr>
<td>Modulus of Elasticity</td>
<td>14200 MPa (Australian/New Zealand Standard AS-2878)</td>
</tr>
<tr>
<td>Density (ρ)</td>
<td>1200 kg/m³</td>
</tr>
<tr>
<td>2nd Moment of area (I)</td>
<td>3.97x10⁸ mm⁴</td>
</tr>
</tbody>
</table>

From Equation 2.13, the first four natural frequencies are;

\[
\begin{align*}
 f_1 &= 1.44 \text{ Hz} \\
 f_2 &= 9.04 \text{ Hz} \\
 f_3 &= 25.31 \text{ Hz} \\
 f_4 &= 49.61 \text{ Hz}
\end{align*}
\]

The above are the theoretical natural frequencies for this particular pole assuming the following.

a. Pole cross section and properties are constant along the height

b. There is negligible effect of cables perpendicular to the line direction.

c. The pole is fixed at the ground level.

While items (a) and (b) can be accounted for, item (c) can be a source of variability in results from one pole to another. The issues with embedded conditions can be illustrated by Figure 2.18, which shows that fixities of the pole at the base may not be at the ground line. If the soil around the pole is not well compacted, there is a very good chance that there would be relative movement between the pole and soil close to the ground line which would affect the pole natural frequency.

In addition, there are several other parameters which would affect the different properties of timber utility poles such as reinforcement and additional restraints, cable loads, transformers, tapering cross section along the height and natural imperfections of timber poles. So, adequate modifications and alterations should be incorporated when performing natural frequency calculation by Equation 2.13. Even though it is not practical
to identify all mode shapes, it may be possible to differentiate mode shapes by comparison of mode shape curvatures.

![Diagram of Timber Pole and Ground Level with spring connections](image)

Figure 2.18: *The different embedded condition of poles to the ground*

Crews et.al. (2004) investigated measuring the in-service flexural stiffness of timber bridges using the dynamic response of timber bridges to an impact load. 40 single and multi-span timber bridge spans were tested to demonstrate the reliability and simplicity of the methodology. They also noted that even though the methodology is capable of assessing the load carrying capacity of bridges, the load is dynamic in nature and its impact on the bridge is not just a function of the magnitude of the load. The surface condition of the bridge deck is a major contributing factor as a smooth surface will allow a much larger load to be carried safely but a similar level load may cause much distress and damage to the bridge if the surface is not sufficiently smooth.

Based on the discussion, it appears that this method could be applied to timber poles. However, the identified limitations need to be considered and further work is required to examine the following issues.

- Possibility of damage identification below ground line.
- Degree of sensitivity of the technique to identify small defects.
- The sensitivity of detecting vibrations by accelerometers from the excitations at the bottom of the timber pole.
Influence of reinforcement and additional restraints on the pole response.
Evaluating the embedded condition of the timber pole.
Establishing of inspection with different obstruction such as pole sleeve/collar to timber pole.
Incorporating the tapering nature of the pole into the calculation
2.5.2 Stress Wave Technique

Stress wave technique is also known as low strain integrity testing. Several techniques that utilize SWP have been researched for use in NDT. Speed-of-sound transmission and attenuation of induced stress waves in a material are frequently used as NDT parameters (Turner, 1997).

To illustrate this technique, consider application of one-dimensional wave theory to a homogeneous viscoelastic bar shown in Figure 2.19.

![Figure 2.19: Viscoelastic bar of length L subjected to an impact](Source: (Ross and Pellerin, 1994))

After an impact is performed at the end of a bar, a wave is generated. This wave immediately begins moving down the bar as particles at the leading edge of the wave become excited, while particles at the trailing edge of the wave come to rest. The wave moves along the bar at a constant speed, but its individual particles have only small longitudinal movements as a result of the wave passing through them. After travelling the length of the bar, this forward-moving wave impinges on the free end of the bar, is reflected, and begins travelling back down the bar.

Energy is dissipated as the wave travels through the bar; therefore, although the speed of the wave remains constant, the movement of particles diminishes with each successive passing of the wave. Eventually all particles of the bar come to rest (Robert et al., 1999).

Monitoring the movement of a cross section near the end of such a bar in response to a propagating stress wave results in waveforms that consist of a series of equally spaced pulses whose magnitude decreases exponentially with time as shown in Figure 2.20.
The propagation speed $C$ of such a wave can be determined by coupling measurements of the time between pulses $\Delta t$ and the length of the bar $L$ using Equation 2.14.

\[
C = \frac{2L}{\Delta t}
\]  

(2.14)

This technique has been successfully used in pile integrity testing for a long time. Indeed, much of the practical knowledge of this method is based on pile testing. However, some of the issues can be equally applicable to timber poles. For a pile or timber utility pole which is embedded within a uniform homogeneous soil, the progress of the stress wave down the pile or up in the pole is affected by the following factors.

- The properties of the pile or pole material itself
- The characteristics of the soil within the pile or pole into which it is embedded, which attenuate the stress-wave in a manner related to the stiffness of the soil.
- Variation in the pile or pole body, either in its external diameter or in its internal properties. Differences in the internal properties or dimensions of the body cause part of the wave to be reflected, while the reminder of the wave continues along the pile or pole. The onward travelling wave is reduced in amplitude in equal proportion to the magnitude of the reflected wave in accordance with the principle of the conservation of momentum.

The calculation of impedance reveals several important characteristics. It is principally a function of the pile cross-section, the propagation velocity of the stress-wave through the pile and the density of the pile material.
Impedance at any given level in the pile is therefore usually expressed by the relationship

\[ Z = \rho C A \]  \hspace{1cm} (2.15)

where;
- \( \rho \) = Density of the pile/pole material
- \( C \) = Propagation velocity of the stress wave
- \( A \) = Cross sectional area of the pile

The propagation velocity is related to the dynamic modulus of the elasticity (\( E \)) and density (\( \rho \)) of the pile material by relationship.

\[ C = \sqrt{\frac{E}{\rho}} \] \hspace{1cm} (2.16)

Thus, by substitution, \( Z \) can also be expressed in the alternative forms given by

\[ Z = \frac{E A}{C} \] \hspace{1cm} (2.17)

\[ Z = A \sqrt{E \rho} \] \hspace{1cm} (2.18)

Equation 2.18 is the most commonly used expression for pile impedance in low-strain integrity testing. Low strain integrity testing is the examination of the response of an embedded pile to an external impulse force imparted by a blow from a light, hand-held hammer or in some cases an electrodynamic shaker. Equation 2.16 is mostly used in dynamic load testing methods. Dynamic load testing methods can be utilised as high-strain integrity test technique. Heavy weights such as a pile driving hammer or similar is dropped on to the head of the pile and the response of the pile is measured during this high-strain integrity testing method.

From standard wave theory, relating to vibrations in long slender rods (Turner, 1997), the resonating length \( L \), of the pile is given by,

\[ L = \frac{C}{2A_f} \] \hspace{1cm} (2.19)
Where;  \( C \) – the velocity of plane wave propagation along the pile  
\( \Delta f \) – the frequency interval between successive resonances

Thus in a perfect straight sided pile in free air with no toe restraint Equation 13 gives the length of the pile.

In practice, the pile-head response is normalized by plotting the value of the pile-head velocity at maximum force \( \frac{v_{\text{max}}}{F_{\text{max}}} \) for each frequency increment. This is to take account of practical variation of the maximum force \( F_{\text{max}} \) which has a corresponding effect on maximum pile-head velocity. The parameter \( \frac{v_{\text{max}}}{F_{\text{max}}} \) is termed Mobility (M) (Equation 2.20).

\[
M(f_1) = \frac{v_{\text{max}}(f_1)}{F_{\text{max}}(f_1)}
\]  

(2.20)

where;  
\( M(f_1) \) = mobility at frequency \( f_1 \)  
\( v_{\text{max}}(f_1) \) = maximum measured velocity at frequency \( f_1 \)  
\( F_{\text{max}}(f_1) \) = maximum applied force at frequency \( f_1 \)

These formulations for piles can be translated to timber utility poles. The impedance of the pole can be determined by Equation 2.15. This impedance is a key factor in assessing the properties of the pole. For a healthy pole, the ratio between \( V_{\text{max}} \) and \( F_{\text{max}} \) will tend towards a constant value over the frequency spectrum under evaluation. Davis and Dunn (1974) called this characteristic mechanical admittance which is dependent on the internal properties of the concrete pile.

This characteristic mechanical admittance (Mobility) is the inverse of the impedance and is given by;

\[
M = \frac{1}{Z} = \frac{1}{\rho CA}
\]  

(2.21)

To assess the applicability of this method to timber poles in Australia, Groundline Pty Ltd performed several investigations involving field testing more than 500 timber poles (Flatley, 2009). In 2005, Groundline tested 450 poles within the Perth metropolitan area in Western Australia. Twenty per cent of poles selected were already classified using
traditional drilling methods as “Unserviceable”. The stress wave analysis was performed with TDR2 Pile Tester with necessary alterations to adapt to timber utility poles. The testing was conducted by hitting the timber pole at the side close to the ground line. This will generate transverse or flexural stress waves in the timber poles. The time domain and the frequency domain were studied to evaluate all pole properties. From this empirical work, it was found that poles with mobility rating not more than $70000 \times 10^{-9}$ m/s/N are structurally satisfactory whereas poles with a mobility rating more than $70000 \times 10^{-9}$ m/s/N are structurally inadequate or near the end of service life of a timber utility pole.

The application of transverse stress wave technology was also successfully used to determine the embedded depths of timber piles by Douglas and Holt (1994). Dai et al. (2011) also reported field investigations undertaken to determine the embedded depths of transmission poles using SWP. It was found that the propagation velocity perpendicular to the grain (or in cross sectional direction) for non-degraded Douglas-fir is approximately 1250m/s, whereas severely degraded members exhibit velocity values as low as 310 m/s (Robert et al., 1999).

Based on the preliminary work performed by Groundline and Swinburne university (2010), it appears that this method of generating transverse stress waves by hitting the timber poles at the side closer to the ground line is very promising in assessing the structural properties of timber poles. The typical SWP testing of concrete piles is conducted by generating longitudinal SWP (compressional waves) by an impulse force on the top surface of the concrete pile. However, further work is required to examine the following issues with stress wave evaluation of timber poles using transverse SWP.

- Degree of sensitivity of the technique to identify small defects.
- Separation of damage identification below and above ground.
- Establishing of wave propagation velocities for different species of timber.
- Influence of reinforcement and additional restraints on the pole response.
2.5.3 Resistance Drilling

Resistance drilling can be used to characterise wood properties and to detect abnormal physical conditions in structural timbers. This is an automated form of mechanical probing of woods. The Resistograph is a mechanical drill measurement that records the relative resistance (i.e. drilling torque) of wood as a rotating drill bit is driven at a constant speed. It produces a chart showing the relative resistance profile for each drill path. This profile can reveal the relative density change along the drill path which is typically used to diagnose the internal condition of structural timbers (Ross et al., 2006).

The drilling resistance $R_D$ (Nm s/rad) is defined as:

$$R_D = \frac{T}{\omega}$$

(2.22)

where; $T =$ drilling torque (Nm);

$\omega =$ angular speed (rad/s)

A resistograph tool consists of a power drill unit, a small diameter drill bit, a paper or electronic recorder. The diameter of the drill bit is typically small and varies from 1.5mm – 3mm, so that any weakening effect of the drill hole on the wood cross section in negligible.

Resistance drilling is generally used to confirm suspected areas of decay identified by visual inspection or sounding test. When decay is suspected or detected with a timber pole, drilling can help inspectors to define the decay’s presence and extent.

Brashaw et al. (2005) studied the accuracy and reliability of a micro drilling resistance tool IML RESI F300-S which is based on the above mentioned technology. The equipment was developed in Germany and was commercially available for the drilling inspection of wood. The primary materials used for the evaluation were bridge timbers containing different levels of natural decay. These timbers were obtained from several sources and had been removed from service for various reasons. Timber bridge girders, pilings, decking and railing components were used.
From this study, each specimen’s resistance chart was captured electronically by the equipment and was accompanied by photographs of the cut-open specimen. An overall analysis of data from all the specimens led to the development of indices of decay for the test specimens, as shown in Table 2.9;

<table>
<thead>
<tr>
<th>Drilling resistance</th>
<th>Deterioration Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>25-100%</td>
<td>Sound wood</td>
</tr>
<tr>
<td>10-25%</td>
<td>Moderate</td>
</tr>
<tr>
<td>0-10%</td>
<td>Severe</td>
</tr>
</tbody>
</table>

These indices are applicable only to Douglas-fir species, which represented nearly 85% of the specimens tested. So, it is necessary to build up all other indices for different species of wood used for timber utility poles. A major limitation of this method is that it only detects damage where the drilling is performed. Hence if the damage is above or below the inspected area it would not be detected. However, it is superior to the currently used drilling method described in Section 2.4.3 which is subjective and leaves greater holes which could eventually lead to deterioration and removal from service.
2.5.4 Ultrasonic Waves

Ultrasonic testing uses high frequency sound energy to detect defects. Ultrasonic inspection can be used for flaw detection, dimensional measurements and material characterization. An Ultrasonic device uses a pulser/receiver that generates a high frequency ultrasonic energy. The sound energy is introduced and propagates through the wood in the form of waves. When there is a discontinuity (such as a crack or decay) along the wave path, part of the energy will be reflected back from the surface of the discontinuity. The reflected wave signal is transformed into an electrical signal by the transducer and is displayed for viewing.

Ultrasonic testing is based on time-varying deformations or vibrations in the materials, which is generally referred to as acoustics. All material substances are comprised of atoms, which may be forced into vibrational motion about their equilibrium positions. Many different patterns of vibrational motion exist at the atomic level. However, most are irrelevant to acoustics and ultrasonic testing. Acoustics are focused on particles that contain many atoms that move in unison to produce a mechanical wave. When a material is not stressed in tension or compression beyond its elastic limit, its individual particles perform elastic oscillations. When the particles of a medium are displaced from their equilibrium positions, internal (electrostatic) restoration forces arise. It is these elastic restoring forces between particles, combined with inertia of the particles that leads to the oscillatory motions of the medium.

In solids, sound waves can propagate in four principal modes that are based on the way the particles oscillate. Sound can propagate as longitudinal waves, shear waves, surface waves and in thin materials as plate waves. Longitudinal and shear waves are the two modes of propagation most widely used in ultrasonic testing. The particle movement responsible for the propagation of longitudinal and shear waves is illustrated in Figure 2.21.
In longitudinal waves, the oscillations occur in the longitudinal direction or the direction of wave propagation. Since compression and dilation forces are active in these waves, they are also called pressure or compression waves. In the transverse or shear waves, the particles oscillate at a right angle or transverse to the direction of propagation. Shear waves require an acoustically solid material for effective propagation, and therefore, are not effectively propagated in materials such as liquids or gasses. Shear waves are relatively weak when compared to longitudinal waves. In fact, shear waves are usually generated in materials using some of the energy from the longitudinal waves.

Different types of ultrasonic waves can be used, but the most convenient for wood identification are bulk longitudinal waves. Ultrasonic images can be reconstructed from all characteristic parameters of the wave such as time of flight, amplitude, frequency spectra of the waveform, the phase, etc. The energy distribution and energy flow are important parameters for enhancing the image contrast (Bucur, 2005). On trees, the equipment for ultrasonic imaging is using frequencies ranging from 50 kHz - 1 MHz. Increase in the frequency adopted increases the image resolution but unfortunately it leads to an increase in signal attenuation. For this reason a good compromise is required between frequency and image resolution.

Sensitivity and resolution are two terms that are often used in ultrasonic inspection to describe a technique's ability to locate faults or defects. Sensitivity is the parameter to
locate small discontinuities. Sensitivity generally increases with higher frequency (shorter wavelengths). Resolution is the ability of the system to locate discontinuities that are close together within the material or located near the surface. Resolution also generally increases as the frequency increases.

The wave frequency can also affect the capability of an inspection in adverse ways. For example, if the selected wave frequency is closer to or at the natural frequency of the system, this results in elevated response from the system, masking the defects to be identified. Therefore, selecting the optimal inspection frequency often involves maintaining a balance between the favourable and unfavourable results of the selection. Before selecting an inspection frequency, the material's grain structure and thickness, and the discontinuity's type, size, and probable location are considered. As frequency increases, sound tends to scatter from large or course grain structure and from small imperfections within a material. Details works have been carried out by B Jozi et al. (2014) looking in to assess and detect defects in timber members using ultrasonic echo methods.

**Acoustic Impedance**

Sound travels through materials under the influence of sound pressure. Because molecules or atoms of a solid are bound elastically to one another, the excess pressure results in a wave propagating through the solid.

The acoustic impedance \( Z \) of a material is defined as the product of its density \( \rho \) and acoustic velocity \( V \).

\[
Z = \rho \times V
\]  

(2.23)

Acoustic impedance is important in;

a) the determination of acoustic transmission and reflection at the boundary of two materials having different acoustic impedances.

b) the design of ultrasonic transducers.

c) assessing absorption of sound in a medium.
Ultrasonic waves are reflected at boundaries where there is a difference in acoustic impedances \((Z)\) of the materials on each side of the boundary. This difference in \(Z\) is commonly referred to as the impedance mismatch. The greater the impedance mismatch, the greater the percentage of energy that will be reflected at the interface or boundary between one medium and another. This property is used to evaluate the discontinued or decayed layers and defects within the inspected material.

Ultrasonic testing is common in the mechanical industry where materials subjected to inspection are homogeneous, regular in shape and have a smooth surface. It is most successful in the inspection of metal products where defects such as cracks or discontinuities are reflected precisely by ultrasonic waves.

From the knowledge and experience of using ultrasonic waves to find defects and discontinuity in material it is found that the application of ultrasonic waves to timber poles is not practical. Ultrasonic wave inspection needs mobilisation of relatively bigger instruments which are more costly than most other techniques. Further, timber poles with their natural imperfection and uneven surface are a major drawback to the application of ultrasonic wave technology. Testing with ultrasonic wave technology for timber will at best provide localised results only. It is impossible to assess the below ground section of the timber utility pole which is always the critical section of a timber utility pole.
2.6 Discussion and Conclusions

Timber poles are used for various purposes such as for street lighting, flood lighting, aerial conductor, traffic signal communication and as multi usage poles. Timber utility poles are selected depending on the purpose and location. There are different parameters governing the design criteria of timber utility poles. These are how the different important classes are derived. Based on the environmental conditions and design criteria the poles are treated differently with respect to satisfying the design service life with minimal interference.

As discussed in detail, the deterioration of timber poles is inevitable. There are a number of factors influences the decay of timber utility poles. In addition to decay, timber experiences wet and dry rotting. The timber can decay in ground and above ground. The in ground decay is more serious as the deterioration is concealed and often left unnoticed during the inspections resulting in the unpredicted failure of timber utility poles. This leads to loss of supplies to critical services and sometime ends in fatal accidents. This situation paves the path for periodical inspection of timber utility poles with a more reliable inspection technique. The replacement of a timber utility pole is a very tedious and time consuming process. A lot of resources and money is spent to replace a pole. Figure 2.22 depicts a typical procedure and the resources involved in the replacement of a timber pole.

![Figure 2.22: A typical timber utility pole replacement in progress](image)

63
Drilling inspection is the common technique along with visual and sounding tests for damage detection of poles in Australia. Usually the drill holes are about 14mm maximum in diameter (Energy Australia, 2006). The periodic drilling inspections would result in a number of holes which cause strength reduction at the critical section of the timber pole. Factors such as smell, colour, drilling resistance, resulting shavings and the bite of the drill are important considerations in a drilling test. Hence, this inspection technique provides subjective results depending on personal observations and level of experience of the inspector.

By comparison micro resistance drilling can be considered to be a non-destructive drilling test. The drill hole is small and has negligible effect on the strength of timber poles. It has the advantage over normal drilling by removing the subjective nature of testing. However, the identification of damage is limited to the drilling locations. This method needs calibration and special consideration for choosing the drill bits. The repetitive drilling action affects the sharpness of the drill bit. So, these need to be frequently replaced or re-sharpened. In addition, resistance indices have to be developed for each and every timber species. Another drawback of this inspection method is the multiple and time-consuming drilling which is required to map the area and extent of the decay. Micro-drilling technology is not practiced in Australia.

Experimental modal analysis has been used for damage detection in structures. The diagnostic parameters of experimental model analysis are natural frequencies, mode shapes and modal damping ratios which can be estimated from the vibration measurements. The presence of damage or deterioration will cause changes in these parameters. Natural frequencies may be measured using a single or few sensors whereas mode shapes requires multiple sensors to be located at different parts of the structure. Some of the most successful results of damage identification through experimental modal analysis have been achieved on laboratory scale structures, where ease of accessibility allows mode shapes to be determined in their entirety (Kosmatka and Ricles, 1999).

Several different approaches were identified with experimental modal analysis such as natural frequency based methods, mode shape based methods, mode shape curvature/strain mode shape based methods, dynamically measured flexibility based methods and matrix update based methods. The physically tangible relation between
stiffness and mass changes and natural frequency changes coupled with ease of measurement of the natural frequencies was the impetus for using modal methods to identify damage. Salawu (1997) reviewed 65 publications dealing with the detection of structural damage through frequency changes. He revealed that the frequency values obtained from periodic vibration testing can be used to monitor structural behaviour and also assess structural condition.

However, many of the proposed methods require either a theoretical model of damage or a set of sensitivity values to be computed before physical measurements (Peter and Fanning, 2004). To be truly realistic, the methods would require consideration of all possible damage events at various locations on the structure. Chen et al. (1995) questioned the effectiveness of using the changes in natural frequencies to indicate damages in a structure. The first four frequencies of a steel channel exhibited no shifts greater than 5% due to a single notch severe enough to cause the channel to fail at its design load. The frequency variation due to incidental/ambient vibration and environmental effects can be as high as 5-10%, they argued that lower frequency shifts would not necessarily be useful damage indicators. Hence, this research creates significant consideration of looking very carefully at the sensitivity, limitation and other influences of relying on natural frequency changes to identify defects within timber utility poles.

The greatest success in the use of natural frequency shifts for damage identification, as evidenced by the number of published examples is in small simple laboratory structures with only single damage locations. The identification of multiple damage scenarios using frequency shifts even for simple laboratory structures is not as effective as evidenced by the scarcity of literature in this area relevant to single damage identification (Peter and Fanning, 2004).

Yan et.al (2014) looked into a different damage detection method based on wavelet packet energies. They validated the method on numerical timber pole models identifying damage severities of structures where measurement sensors cannot be placed in the damage region, such as the studied embedded timber poles. The results of the study had limited success showing a clear trend of the proposed damage index and some outliers in the obtained indices. Hence, a more refined damage classification method was required to
will be developed in the future so that the damage severity indicator will be more effective.

SWP is widely used in the piling industry for the non-destructive evaluation of concrete piles. Speed of sound transmission and attenuation of induced stress waves in materials are frequently used as the key parameters. There has been research conducted using stress waves to evaluate structural stability of timber bridges. The presence of decay greatly affects the stress wave transmission time in wood. It was noted that stress wave transmission times perpendicular to the grain are drastically reduced when the member is degraded (Robert et al., 1999). Transmission times for non-degraded Douglas-fir are approximately 800 μs/m (1250m/s), whereas severely degraded members exhibit values as high as 3,200 μs/m (312.5m/s) or greater. A 30% increase in stress wave transmission times implies a 50% loss in strength (Robert et al., 1999). Transverse travel paths are best for finding decay. Parallel-to-grain travel paths can bypass regions of decay.

Ultrasonic inspection is widely used in the mechanical industry, especially inspecting metal parts. Anyway, there is some evidence of ultrasonic inspection being used for the evaluation of standing trees (Morales Conde et al., 2014). A gradually decreasing ultrasonic wave travel time indicates that the level of decay along the section of the wood. The region between advanced decay and sound wood is labelled as the transition zone of the tree. Ultrasonic Inspection is a very useful and versatile non-destructive testing method in the mechanical industry. Some of the advantages of ultrasonic inspection that are often cited are listed below.

- Ultrasonic inspection is sensitive to both surface and subsurface discontinuities.
- Only single-sided access is needed when the pulse-echo technique is used.
- It is highly accurate in determining reflector position and estimating size and shape the reflector.
- Electronic equipment provides instantaneous results.
- It has other uses, such as thickness measurement, in addition to defect detection.

As with all non-destructive testing methods, ultrasonic inspection also has its limitations, which are:

- Surface must be accessible to transmit ultrasound. This disables the inspection of the below ground pole section which is also an important part to be evaluated.
Skill and training is more extensive than with some other methods.

Poles that are rough, irregular in shape, exceptionally thin or not homogeneous are difficult or inappropriate to inspect.

Linear defects oriented parallel to the sound beam may go undetected.

Reference standards are required for both equipment calibration and the characterization of defects.

As discussed up to now, there are advantages and limitations with every inspection technique. Based on the review, from the identification of limitations and advantages of each method, it appears that the Stress Wave Technique method offers the best potential for success in timber pole application. As it is discussed, the stress wave technology has been deployed very successfully in the non-destructive evaluation of concrete piles in the construction industry for a long period now. The stress wave pile inspection results are acceptably accurate, to a certain limit, and widely adopted by many countries in the world. There has been some research carried out for using stress wave technology to inspect timber utility poles. However, there is still no remarkable stress wave based inspection instrumentation available in the commercial arena for the non-destructive inspection of timber utility poles. Based on the preliminary work from Groundline limited, the SWP holds great potential as a tool to be developed for use in damage detection and assessment of timber utility poles. Therefore, the application of stress wave technology for timber utility poles will be investigated thoroughly in the following chapter.
Based on the detailed study of current inspection techniques it is very clear that asset managers need an alternative non-destructive inspection technology. The new inspection technique should have the ability to produce accurate, reliable and repeatable results while the inspection process should also be rapid and less expensive compared to the current inspection techniques.

As presented in Chapter 2, it is clear the stress wave technology has excellent potential to non-destructively assess timber utility poles. The stress wave technology as used in the piling industry appears to be accurate and reliable compared with most of other inspection techniques. Further, the stress wave inspection process is relatively rapid. This chapter details the principles of SWP technology, its usual application and how to adopt the technique for the non-destructive investigation of timber utility poles.

### 3.1 Stress Wave Propagation

The science of SWP involves the study of generating, transmitting and receiving the energy from impact in the form of vibrational waves in materials. Generally, the very common practice of this technology around the world is adopting the longitudinal directional SWP. This technique is also called Low Strain Integrity Testing because the stress waves are generated by a small mechanical excitation. This longitudinal directional SWP testing has been successfully used for a long time for the integrity testing of reinforced concrete piles. The SWP velocity and reflections are the key parameters in stress wave testing. These parameters are affected by the properties of the medium the wave travels through and the physical conditions such as presence of cracks or discontinuities. Stress wave testing has been examined as a technique for evaluating structural stability of timber bridges (Haldar et al., 2000). Earlier, it was found that the stress wave speed and attenuation could be used successfully to predict the static tensile
and flexural properties of timber (Ong et al., 2006). The presence of decay greatly affects the SWP velocity in timber.

Typically, the integrity of a concrete pile is examined with stress waves generated in the longitudinal direction. The testing is conducted using excitation in the longitudinal direction of the concrete pile from a small hand held hammer. Usually this impact hammer weighs between 1-2kg. The pile response is recorded by means of a geophone or velocity transducer at the surface of the pile in the longitudinal direction. The geophone mainly records the compressional stress wave response even though there are other wave components such as dispersive waves, surface waves and shear waves. Both the input impulse force and the output velocity response are recorded. These parameters are then analysed both in the time domain and frequency domain.

### 3.2 Longitudinal Wave Propagation

The longitudinal SWP technique is mainly concerned with the compressional waves which are generated from the impulse in the longitudinal direction. This compressional stress wave technology is adopted for non-destructive testing of concrete piles. The application and the theory of compressional stress wave technology in NDT is less complicated and straightforward in detecting damage and travels relatively faster than transverse waves.

The propagation of stress-waves through a concrete pile is based on the fundamental concepts of dynamics of the impact of elastic bodies. The principle of conservation of momentum is represented by the following equation (Turner, 1997).

\[
m_1v_1 + m_2v_2 = m_1u_1 + m_2u_2
\]

(3.1)

where;

- \(m_1, m_2\) - Masses of two impacting bodies
- \(u_1, u_2\) - Velocities before impact for \(m_1\) & \(m_2\) respectively
- \(v_1, v_2\) - Velocities after impact for \(m_1\) & \(m_2\) respectively

Further, Newton’s experimental law relating to the impact of elastic bodies is expressed by the following equation.
\[
\frac{v_1 - v_2}{u_1 - u_2} = -e
\]

where; \( e \) - the coefficient of restitution

For perfect elastic bodies the coefficient of restitution \( e = 1 \). Bodies which have zero coefficient of restitution (i.e. no rebound) are called inelastic bodies.

SWP can be visualised conceptually by the behaviour of spheres joined by springs when subject to impact. Typically, SWP through a free ended pile can be modelled as shown in Figure 3.1. The stress wave propagates downwards though the pile towards its toe as compressive waves. As they reach the toe of the pile, particles on the plane which are free ended, transform into tensile mode and pull downward the particles above the plane again. This tension wave propagates towards the head of the pile pulling every particle located above it towards the toe. Hence, a reflected wave in a free ended pile will result in surface movement of the pile head in the same direction as that caused by the initial impulse. In other words, stress wave velocity of the initial and returning waves will be in the same direction for a free ended pile.

Figure 3.2 shows the model of a fixed ended pile with spheres connected with springs. In this case, the initial compressive wave reaches the toe, the particles in the plane rebound from the rigid elastic surface at the toe of the pile and motion is reflected as a compression wave again in the upward direction (towards the head of the pile). When the compression wave returns to the surface the head is impelled in an opposite direction to that imparted by the original impulse. In other words, the SWP direction will be in the opposite direction for a fixed ended pile.

**Figure 3.1: Impact of elastically connected spheres with no end restrains**

*(Turner, 1997)*
It can also be inferred that in a perfectly elastic system, the motion would be repeated cyclically. An idealized time domain response for an intact free ended and fixed ended pile is shown in Figure 3.3. Moreover, it can be concluded that a relative loss or increase in section will induce characteristic responses which if measured by a transducer placed on the pile head and analysed, can be interpreted in terms of the change of section (Figure 3.4). This is the basic concept of the pile response in the time domain.

This longitudinal direction SWP velocity mainly depends on the material properties of the medium in which it is traveling. These properties are the Young’s Modulus of Elasticity ($E$) and density of the material ($\rho$). The longitudinal SWP velocity ($C_L$) is determined by Equation 3.3 (Turmer, 1997).

$$C_L = \sqrt{\frac{E}{\rho}}$$  \hspace{1cm} (3.3)
It is found that applying a longitudinal wave to a standing timber utility pole requires additional mechanical assistance and human resources. The mobilization of the equipment and the inspection would consume a lot of time. Consequently, it would likely not be cost effective to adopt this approach as an alternative non-destructive
inspection technique. Hence, the application of transverse directional impact to create transverse stress waves closer to the ground line level would be a more practical solution to use the SWP technique for timber utility poles. The issues and processes involved in the transverse SWP is discussed in the following section.

### 3.3 Transverse Wave Propagation

The transverse wave propagation technique is associated with shear waves and dispersive waves. These are generated from impulse in the transverse direction to the member being investigated. Dispersive wave propagation was investigated to determine the length of installed timber piles by Douglas and Holt (1994). Kim et al. (2000) also evaluated the structural condition of timber piles using transverse stress waves. The velocity of transverse stress waves ($C_T$) mainly depends on the Shear Modulus of Elasticity ($G$) and the density of the material ($\rho$) (Razvan, 1999).

$$C_T = \sqrt{\frac{G}{\rho}}$$

(3.4)

The Shear Modulus of Elasticity can be derived from the following fundamental equation of linear elasticity.

$$G = \frac{E}{2(1+\nu)}$$

(3.5)

where;

- $E$ - Young’s Modulus of Elasticity
- $\nu$ - Poisson's ratio

### 3.4 Application of Transverse Waves to Timber Poles

Based on the knowledge of using compressional SWP in concrete piles, the application of transverse SWP is now investigated as a technique for damage detection of timber utility poles. Several types of stress waves are generated whenever a solid with a bounded geometry is struck. As discussed earlier, striking in the transverse direction will generate bending waves along with longitudinal compressional waves and surface waves. However the bending waves contain a high percentage of the total energy of the wave motion (Douglas and Holt, 1994). Further, detailed assessment timber utility poles
using the guided waves in both longitudinal and transverse direction are carried out by Yan et al. (2014).

It is critical to understand the SWP pattern when a timber utility pole is hit transversely. It is also important to decide where the pole needs to be struck to get the SWP velocity trace. From the field trials, it was found that striking the pole closer to the ground reduces unwanted noise and will be a fixed reference point for calculating the below ground and above ground lengths of a timber utility pole from the SWP velocity trace.

Figure 3.5 shows a typical schematic SWP pattern for a timber pole being inspected in the transverse direction. The above discussed points are marked in a typical SWP trace of a timber utility pole in Figure 3.6. The selection of these points is explained in Section 5.2.
The stress waves in the transverse direction are generated by striking the pole with a hammer instrumented with a load cell which measures the impact force. The stress wave response due to the impulse is measured with a geophone at the base of the pole close to the ground. It is essential to have a sufficient impulse force to get a meaningful SWP measurement. When sufficient energy is transferred into the timber utility pole by the impulse, the stress waves travel along the full length of the pole and are reflected from both ends of the pole. There will be intermediate reflections if there are any irregularities along the pole length such as section reduction and change of property of the pole.

Based on field testing of number of poles, it was found that a minimum impulse force of 2.5kN (refer Section 5.4) is required to obtain reasonable SWP velocity traces of timber utility poles. Further, from the field testing, the transverse SWP velocity for timber utility poles falls roughly between 800m/s – 1300m/s. The total length of Australian and New Zealand timber utility poles varies from 6.0m – 18.5m. Hence, the total time of velocity trace recorded for one cycle of SWP will be limited between 0 – 45ms. To get a good resolution of the velocity trace, the time step needs to be in the range of 40 – 50μs. In other words, the frequency of the system recording the trace needs to be between 20 – 25kHz. The duration of impulse force input varies up to 3ms while
the impulse force itself may go up to a maximum of 8500N. The above time step parameter set for recording the velocity trace is able to capture the impulse time history to a sufficiently good resolution.

The parameters discussed above from the requirements to consider when assembling the Beta pole tester. There should be sufficient CPU and memory capabilities to capture the 20 – 25kHz frequency data over a period of 0-75ms in the tester. The velocity and impulse force are recorded at the same time while the inspection is conducted. Hence, the data acquisition system needs to have at least two input channels as one is needed for the impulse hammer and the other for the geophone. As the inspection of poles occurs throughout the whole day in the field, the power supply for the unit should have the capacity to run throughout the whole day. Similarly, the storage of the computer should be sufficient to record the results of a whole day’s testing. Taking consideration of these requirements, a list of hardware components used in the Beta Pole Tester developed is as follows:

- Impulse Hammer
- Geophone
- Analogue to Digital & Data recorder
- Toughbook Computer

The Beta Pole Tester pack deployed for testing timber utility poles using SWP technique is shown in Figure 3.7.
3.5.1 Impulse Hammer

For the Beta Pole Tester, a 1.2kg impulse hammer is used. This fibre glass shafted hammer is approximately 30cm in length, with built in constant current load cell. It is fitted with a polymer tip suitable of generating up to a 1000Hz excitation frequency. The hammer is capable of exerting up to 10kN of impulse force. This impulse force capability of the hammer will satisfy the normal required amount of energy to inspect a timber utility pole using SWP. Figure 3.8 shows the impulse hammer used in this Beta pole testing unit. The necessary power for the hammer and the geophone is supplied from the Analogue to Digital Convertor & Data recorder unit.
3.5.2 Geophone

The geophone used in this research is an omni directional, low frequency velocity transducer capable of measuring the velocity in any direction. It has a natural frequency of 4.5Hz and a typical spurier frequency of 140Hz. The standard coil resistance is 375Ω and the nominal output is 28.0V/m/s. The geophone is shown in Figure 3.9.

![Figure 3.9: Omni directional geophone](image)

3.5.3 Analogue to Digital & Data recorder

The above impulse hammer and geophone are connected to an analogue to digital convertor & data recorder (digital signal processing unit) “DataPhysics Quattro” which has up to 40 kHz sampling rate. This unit can be powered by a USB power supply from a computer. The Quattro unit is also capable of supplying the constant current for the operation of both the hammer and geophone. This unit is ultra-portable and rugged and has 4 input and 2 optional output channels. This unit is controlled with SignalCalc software. Figure 3.10 shows a photo of DataPhysics Quattro unit. The SignalCalc interface is used to control the sampling rate, duration, channel controls and other functions. A view of a typical SignalCalc interface is shown in Figure 3.11.
3.5.4 Toughbook Computer

The SignalCalc programme is installed on a field Toughbook computer (Figure 3.12). This unit can run for approximately 10 hours with one charge for testing timber utility poles. The inbuilt GPS module of this Toughbook assists to cross match each timber utility pole tested with its data from the asset data base kept by the electricity network owners of the pole being tested.
Figure 3.12: Field Toughbook computer
3.6 Data collection and digital signal processing

The SWP traces are collected by striking timber poles with the impact hammer and measuring the SWP traces with a geophone as discussed in the preceding section. The location of the hammer and geophone relatively to each other on the pole being tested is very important because the positioning of these components evaluates the pole lengths and possible defect locations. The positioning of the geophone and hammer locations is discussed critically in the following section. Initially the hammer and the geophone are kept at the same level of the pole closer to the ground. For transverse SWP inspection, the most suitable location on the timber utility pole is found from field trials. By locating at a point closer to ground on the pole for hitting with the hammer and receiving the SWP traces with the geophone will eliminate unwanted external noise generated by the hammer. By placing the geophone diametrically opposite to the hammer strike location on the pole, it becomes easy to eliminate the geophone recording the surface waves generated by the hammer impulse on the pole.

The raw data recorded during testing needs to be processed to assess the integrity of the timber utility pole. This is a more crucial exercise because of the stress wave being in the transverse direction and the dispersive nature of the SWP. A typical SWP velocity trace for a timber utility pole is shown in Figure 3.13. The velocity trace has very low frequency noise embedded within it. This is due to the first or second mode of vibration of the timber utility pole which usually varies below 10Hz.

In some other instances, there will be very high frequency noise which results from the resonance of the geophone. It was found that a point impulse loading will produce Rayleigh waves near the point of inspection (Seron et al., 1990). This will end up as multi reflections in the trace recorded. This effect can be interpreted erroneously as noise or other anomalies.

There are a few recognised methods to filter and eliminate unwanted noise from the raw field trace which utilise Fast Fourier Transform (FFT) such as: the Short Kernel Method (SKM), the Continuous Wavelet Transformation (CWT), the Hilbert Transform (HT) or the Laplace Transform (LT). However, it was found that the Fast Fourier Transform and the Short Kernel Methods are effective in interrogating dispersive wave propagations (Chen, 1995). Nancy and Stout (1998) have investigated the use of SKM and CWT to
determine the embedded lengths of electricity timber poles. More detailed work in using wavelet transformation to determine the embedment depth of timber poles and piles are carried out by Yan et al (2014).

Consequently the following section describes in details the FFT and SKM noise reduction and filtering methods for test records.

![Field trace](image)

*Figure 3.13: Typical field velocity trace*
3.6.1 Fast Fourier Transform

The variation of a measured time verifying quantity such as the velocity and impulse force data in the frequency domain is obtained by applying FFT to the time domain data. The analysis in the frequency domain will show the distribution of input energy and the velocity response against frequency. The impulse force distribution of a hammer hit in the time and frequency domains is shown Figure 3.14. It is clear from the figure that the impulse force varies with time which reaches a maximum and decreases to zero. The higher frequency energy input is low and when it passes about 1000Hz, the energy input is almost negligible. Due to this varying nature of the impulse in both the time domain and frequency domain, there will be different components of SWP velocities generated with different frequencies.

Consequently, it is clear from Figure 3.14 that the impulse force at the lower frequencies is more energetic and significant for the stress wave to travel the full length of the pole. However, the energy from the impulse force at higher frequencies becomes very low and insufficient for the wave to travel along the pole. Hence the results or outputs are inappropriate when SWP velocities are in the higher frequency range. The strongest SWP velocity will be representing the lowest frequency range of the impulse. From the field testing, it is found that a reasonable impulse energy input is imparted to timber poles when the frequencies are around 750Hz and below. The data tends to lose impulse energy when the frequency exceeds 1000 Hz. In practice high frequencies can be automatically filtered out using appropriate band pass filters (Liao and Roesset, 1997).

Figure 3.14: Temporal and spectral impulse force input data
3.6.2 Short Kernel Method

Short Kernel Method (SKM) is widely used for processing dispersive waves. This method allows users to determine the phase velocities in dispersive wave signals recorded from transverse impulse testing. In addition, as shown in Figure 3.13, low frequency noise can be effectively removed by using the SKM. The following section discusses in detail the theory of SKM and its application.

Theory of Short Kernel Method

Bendat and Pitrisol (1980) described the procedure for implementing SKM. It is a frequency-dependent scanning operation based on the cross-correlation procedure. Many types of stress waves are generated when a solid with a controlled geometry is struck. As discussed in previous sections, the waves include longitudinal, shear, surface and bending waves. These waves will be dispersive in nature.

Striking a timber pole transversely to its longitudinal axis creates two separate sets of bending waves. One set travels upward toward the tip of the pole where it is reflected and sent downward along the pole. The second wave set travels towards the pole’s embedded butt where it is reflected and sent back upward. These two wave sets traverse the length of the pole one behind the other, reflection after reflection, until they eventually die out.

It is found that if bending weaves are not dispersive, it would be possible to simply measure the distance between two characteristic features of a wave directly with the geophone. In contrast, to find waves speeds and travel times for a dispersive wave, one must first find these quantities for a chosen range of the wave’s harmonic components.

Separating a dispersive wave into its harmonic components to determine the phase velocities of its individual frequencies, and the time they take to travel a pole's length, can be accomplished by either of two signal-processing techniques: the Fourier phase Method or SKM. Both of these methods have been used in dispersive signal analysis. SKM is a digital signal processing method developed by Dr. R A Douglas and his associates (1994) for finding the wave speeds of dispersive signals recorded from inversely layered media.
Jozi et. al. (2014) studied the conventional stress wave-based method that analyses longitudinal waves is the Sonic-Echo method and a typical signal processing method for the analysis of bending waves, the Short Kernel Method. They found that the application of the SKM for bending wave data analysis showed that the reflection peak detection is not an easy task and heavily relies on the experience of the test performer and the signal processor, and availability of prior knowledge of the inspected timber pole.

The following equation explains how to get the SKM trace for a recorded dispersive wave trace.

\[
S_k(t) = \sum_{i=0}^{n-1} x(t + i\Delta t)f_k(i\Delta t)
\]

where;

- **\(S_k(t)\)** - Data point from the SKM transform at the assigned \(k\)th kernel frequency
- **\(i\Delta t\)** - Data point from the SKM kernel at assigned \(k\)th kernel frequency
- **\(x(t)\)** - Data point from real time record
- **\(t\)** - Data point location at real time axis
- **\(k\)** - Index of assigned SKM kernel frequency
- **\(n\)** - Total number of data point in the assigned SKM kernel
- **\(i\)** - A counter associated with \(\Delta t\) as \(i\Delta t\) in SKM kernel
- **\(\Delta t\)** - Time step at real time record and SKM kernel

The above equation for SKM can be understood easily from the Figure 3.15 and from the following worked example. Consider a typical pole SWP velocity trace given by \(x(t)\) in Figure 3.15. The primary resonance frequency could be found by applying FFT to the velocity trace. This resonance frequency will be the kernel seed \((k)\) frequency. The total number of data points in the kernel seed \((n)\) will be 14 for the example considered.

Hence the SKM modified data points will be as follows;

1st SKM data point: \(S_k(t_1) = \sum_{i=0}^{13} t_{(1+i)} k_{(1+i)}\)

2nd SKM data point: \(S_k(t_2) = \sum_{i=0}^{13} t_{(2+i)} k_{(1+i)}\)
\[ S_k(t_n) = \sum_{i=0}^{13} t_{(n+i)} k_{(1+i)} \]

The SKM kernel seed \((k)\) could be a sine, cosine or other function which has the same time step as the real time record data. The kernel seed is the computational form of a function that is being applied to processing of a signal. This digital signal process will be very useful to eliminate the low frequency noise merged with the raw test data. Figure 3.16 shows the application of the SKM methods to typical field tested data. At this particular instance, a low frequency noise is embedded with field test result. The application of SKM which is shown in Figure 3.16, effectively eliminates the unwanted noise from the signal and brings the trace nice and flat along the velocity zero line. As a result of this, the response/reflection for the impulse will be clearly identifiable. Hence, the initial length assessment, below ground depth and damage identification process is easier and more accurate to identify.

Figure 3.15: Pole velocity trace and applied SKM kernel seed

In the process of applying SKM, it is the user’s understanding of selecting a suitable index of SKM kernel frequency \((k)\) and the number of cycles. Effectively the SKM will normalise the signal to the chosen kernel frequency. As a result, this will eliminate or
minimise the effects of unwanted low frequency noise embedded within the original trace. Exploring a suitable kernel frequency and cycles, it is found that a 750/1000 Hz kernel with 1 cycle sine function will be more suitable parameters for SKM filtering of transverse stress wave analysis of timber utility poles.

![Field velocity trace](figure3.16.png)

*Figure 3.16: Comparison of field (original) data and SKM filtered data*

### 3.6.3 The Pole Tester Software Development

The purpose of developing a software interface is to automate the collection of raw data from the Beta pole tester (field timber pole inspection pack) and analyse the results. As discussed earlier for the time domain calculations and the FFT or SKM application, it is very convenient to develop a simple computer program to apply the algorithms and process the SWP velocity traces.

The time domain analysis software of timber utility poles is developed using MATLAB coding to carry out the Fast Fourier Transform function and Short Kernel Method (SKM) signal processing on collected velocity and impulse force traces. The application of SKM is necessary as discussed in Section 3.6.2. In addition, lower and upper frequency filters can be applied to the velocity trace to eliminate any unwanted local noise embedded with the collected signal. The control panel of the pole analysis software is shown in Figure 3.17.
The output window as shown in Figure 3.19 consists of pole data, plots for velocity and force in the time domain, force in the frequency domain and mobility plot. This research study is only looking into the time domain data. A user can insert data flags on the Velocity-Time domain plot to get the certain time values at peaks representing the tip, total reflection points and suspected defective points. In addition, analysis of the impulse applied by the hammer is discussed in Section 5.4.

The MATLAB interface and applied mathematical algorithm coding details are in Appendix G.

![Figure 3.17: Interface: Post analysis of timber pole test results](image)
Figure 3.19: Typical output for a tested pole processed through MATLAB coding.
3.7 Summary and Conclusion

This chapter discusses in detail the stress wave theory and its application as a non-destructive inspection technique for timber utility poles. The application of longitudinal SWP is based on compressional SWP which has been successfully used for the integrity testing of concrete piles. However, the application of longitudinal directional stress waves is not practical for timber utility poles due to the difficulty in accessing the top of the pole for striking it with an impact hammer. Hence, the stress wave is applied in the transverse direction for investigating the integrity of embedded timber utility poles.

The hardware components and the requirements for a timber utility pole field inspection tool are discussed in detail. This was accomplished based on the field trials conducted on a number of timber poles using a TRD2 pile tester, modified to suit the application of transverse SWP. From the knowledge gained from the field trials and requirements, a Beta pole tester was developed. The Beta pole tester is capable of collecting and saving SWP pole inspection data over a month long of field testing. The Beta pole tester can run continuously for a whole day when fully charged enabling the inspection to be carried out without any interference.

The Fast Fourier Transform (FFT) and Short Kernel Method (SKM) data processing tools and algorithms are also discussed in this chapter. Application of FFT and SKM are important to analyse the SWP velocity traces effectively because they are dispersive in nature from transverse directional impulse force. A computer aided software tool is introduced to process the field traces from the field inspection unit and to apply the necessary filters. This software eliminates the time consuming component of processing and analysing the SWP velocity traces of timber utility poles, semi-manually.

The following chapter discusses the utilisation of ANSYS 12.1 FE software to understand and validate the SWP in concrete piles and timber utility poles in the longitudinal direction with and without defects. Further, the transverse directional SWP pattern is investigated in timber poles using the FE models and validated with controlled field tests results. SWP field inspection results for defective in-service timber utility poles are also analysed and discussed in the next chapter. These results are benchmarked by removing the timber utility poles from service and conducting destructive examination of the poles in Powercor’s poleyard.
Chapter 4. FE ANALYSIS AND FIELD TESTING OF TIMBER UTILITY POLES

In this chapter the Finite Element (FE) method is used to model and analyse timber utility poles when subjected to SWP. FE models of timber utility poles with embedded in soil are used to predict the transverse SWP for in-service timber utility poles with different properties. In addition, FE models are also used to study in detail the SWP patterns for different types of defects and damage. Three dimensional orthotropic FE models are created using the ANSYS 12.1 (2010) FE program to replicate timber utility poles embedded in the ground. The results obtained from the field testing of timber utility poles are then benchmarked against these FE models.

4.1 Model Development

FE modelling is a useful tool to explain the SWP in both the longitudinal and transverse directions in timber poles. Further, FE analysis can be effectively used to validate experimental results (or vice versa) and to perform sensitivity studies.

There have been a number of studies carried out using FE models in relation to the integrity testing of concrete piles. The stress wave testing of concrete piles is primarily associated with longitudinal SWP. Kolsky (1963) studied the propagation of stress pulses through viscoelastic rods both analytically and experimentally. Seron et al. (1990) considered the FE method as the best solution to full scale elastic wave equations. They found the main advantage of the finite element model (FEM) approach is its versatility to fit the characteristics of each problem. In particular, FEM allows the use of non-uniform grids, having elements with varying characteristic size, geometry and order of approximation. Further, studies of transient wave propagation in plates were carried out to establish a basis for the impact-echo technique (stress wave propagation) as a non-destructive test for flaw detection in concrete (Sansalone et al., 1987). They concluded that the finite element method demonstrated the potential for becoming a
powerful tool for understanding the interaction of stress waves with defects within solids. Greimann et al. (1987) developed an algorithm based on a nonlinear finite element procedure to study piling stress and pile-soil interaction in integral abutment bridges.

These studies have proved the applicability of FE modelling in accurately reproducing stress wave propagation and reflections for various concrete pile conditions. The same techniques are applied to timber poles in this study. The following sections cover the development and utilisation of the modelling approach for both longitudinal and transverse SWP.

4.1.1 Elements selection and description

In order to develop sufficient confidence in the FE modelling strategy, a typical concrete pile was analysed to verify the SWP characteristic of using ANSYS 12.1 FE software. Typical properties of concrete and soil adopted in the modelling are as given in Table 4.1 from Australian Standard (AS1170.1). The concrete pile and the soil were modelled using the elastic SOLID45 element. This 3D element is defined by eight nodes having three degrees of freedom at each node, translations in the nodal x, y, and z directions. The element has plasticity, creep, swelling, stress stiffening, large deflection, and large strain capabilities (Bendat and Piersol, 1980).

Analysis of piles usually starts with understanding of the soil-pile interaction. Soils, in general are non-homogenous materials that are found in layers along the pile length and each layer may have different properties from the next layer. The soil-pile interaction will not have the same behavior all along the pile shaft. Therefore, variation in soils properties has to be taken into consideration. This variation is very important for calculating the pile load carrying capacity and the design.

The modulus of subgrade reaction, which was originated by Winkler in 1867, is one of the most commonly used methods in pile analysis. In this method, the surrounding soil to the embedded pile can be replaced by a series of vertical and lateral springs to represent both the longitudinal and lateral soil resistance. The spring properties are usually obtained from the load-displacement curves that represent the resistance force as a function of the displacement in the force direction.
ANSYS 12.1 has several multi-purpose spring elements with different capabilities. COMBIN39 is a unidirectional element with a nonlinear force-deflection capability that fits different types of analysis. Jaradat (2005) successfully used the ANSYS COMBIN39 element as a non-linear spring element to represent soil-pile interaction. The spring element COMBIN39, with simplified properties from their study, was used in this research to represent the soil-pile and soil-pole interaction. The element can be defined by the input of the force-deflection data points for both tension and compression.

During stress wave analysis, the impulse force applied to generate the stress waves in the longitudinal or transverse direction is not sufficiently high enough to develop any relative deflection or displacement between the pile-soil or pole-soil interface. Hence the spring element used in this analysis will be a bi-linear COMBIN39 element. The spring element will have a small initial compression stress property and no tension properties.

4.2 Propagation of Longitudinal Waves

Initially, the FE analysis of SWP is performed in the longitudinal direction for concrete piles. The SWP results are well known for concrete piles which will be used to validate the finite element modelling. After the successful verification of SWP in the longitudinal direction with concrete piles, timber utility poles are analysed for the same longitudinal direction wave propagation. From there, the timber poles are then analysed for SWP in the transverse direction.

The soil-pile behaviour can be classified into two categories.

- The first category is axial load-friction behaviour, in which a unique relationship is assumed between the skin friction, shear stress and the relative deflection between the soil and the pole at each depth. This will be the longitudinal wave propagation scenario.

- The second category is lateral load-displacement behaviour, for which the pile is subjected to a lateral soil pressure when it is battered or has lateral loading in the form of shear or moment applied at the top. This modelling will represent the transverse SWP analysis condition discussed later in this chapter.
4.2.1 FE Analysis of a Concrete Pile

The purpose of the analysis is to verify the propagation pattern for an intact concrete pile in the longitudinal direction. A 3D model in ANSYS12.1 was developed to get the FEM simulated SWP velocity results to the following concrete pile. A 6.0m, free ended, 350mm diameter short concrete pile is analysed in the longitudinal direction to verify the SWP. Free ended pile means a friction pile which is not socketed into the rock layer. The pile will have soil friction from the side wall and end bearing from the soil at the bottom of the pile. It is assumed the pile has an upstanding height of 0.5m and 5.5m embedded into the ground. A 2mx2m wide and 10m deep soil section is taken as the boundary condition for the pile. It was found that the SWP in time domain is not significantly affected by the pole soil interface and the soil block size. The soil faces on this boundary are fixed in displacement and rotation. The concrete material properties and the soil properties used for the analysis, as in Table 4.1 are taken from Australian Standards (AS1170.1). The geometrical detail of the pile and the applied idealised impulse force are shown in Figure 4.1. The peak applied impulse force was 4000N and the duration was 1ms which is usually found from SWP pile testing results. The longitudinal direction SWP velocity was calculated as 3541m/s from Equation 3.3.

The transient analysis with ANSYS 12.1 was set to have a fine time step increment of $5 \times 10^{-5}$ s to capture the full SWP trace. For example, in this analysis of a concrete pile, the calculated SWP velocity from Equation 3.14 is 3541m/s. So, with $5 \times 10^{-5}$ s time increment the stress wave could travel a distance of $3541 \times 5 \times 10^{-5} \text{ m} = 0.18\text{ m}$. If a longer time step increment is used, there is a possibility of missing some characteristics of the concrete pile. If we choose a very small time increment step, the ANSYS simulation will run for a long time to complete the analysis. Hence, it is important to choose a suitable time increment step. The impulse force was applied at the top of the concrete pile and the SWP velocity was also measured at the top of the pile.

The SWP pattern is explained schematically in Figure 4.2. Point 1 is at the initial impulse and that is where the stress waves are generated and starting to travel down the concrete pile. Point 2 is the first return of the stress waves reflected from the bottom of the pile reaching the top surface of the pile after the initial impact. The waves will continue to travel again towards the bottom of the pile reflected at the top surface. At
point 3, the second reflected wave from the bottom of the pile will reach the top of the surface. This cycle will continue until the waves die down due to damping. There would not be any intermediate reflection because there are no defects or damage introduced to the pile.

Table 4.1– Material properties used in the analysis of concrete pile

<table>
<thead>
<tr>
<th>Material</th>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete</td>
<td>( f'_{c} )</td>
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</tr>
<tr>
<td></td>
<td>Young’s Modulus</td>
<td>30100 MPa</td>
</tr>
<tr>
<td></td>
<td>Density</td>
<td>2400 kg/m(^3)</td>
</tr>
<tr>
<td></td>
<td>Poisson ratio</td>
<td>0.20</td>
</tr>
<tr>
<td></td>
<td>Calculated Velocity</td>
<td>3541 m/s</td>
</tr>
<tr>
<td>Soil</td>
<td>Young’s Modulus</td>
<td>400 MPA</td>
</tr>
<tr>
<td></td>
<td>Density</td>
<td>1800 kg/m(^3)</td>
</tr>
<tr>
<td></td>
<td>Poisson ratio</td>
<td>0.45</td>
</tr>
</tbody>
</table>

Figure 4.1: Pile geometry and idealised applied impulse force

Figure 4.3 shows the SWP velocity trace in the longitudinal direction for the concrete pile analysed. The velocity is recorded at the top of the concrete pile. In Figure 4.3, the points marked as 1, 2 and 3 show the x-axis time value in seconds. Based on calculated propagation velocity 3541 m/s from Table 4.1, the total length of the concrete pile is
determined as 5.85m from the impulse to 1st reflection. The length of the pile is 6.10m calculated from the 1st reflection and the 2nd reflection times. The calculated length varies from the actual length of 6.0m due to the time step increment. We have already discussed the variation to within 0.18m. In Figure 4.3, Point 1 is the initial response when the impulse is applied. Points 2 and 3 are the first and second full reflections from the bottom of the pile.

The initial few milliseconds of the trace exhibit lot of variation in SWP velocity. This is mainly due to the Rayleigh waves from the surface of the pile top. Hence, it is hard to judge the wave propagation for any reflection from defects with the starting component of a SWP velocity trace.

![Diagram of Points related to the SWP reflection as measured at the top of the pile](image)

*Figure 4.2: Points related to the SWP reflection as measured at the top of the pile*
Figure 4.3: SWP trace of an intact concrete pile as measured at top of pile
4.2.2 FE Analysis of Concrete Pile with Defect

Following the successful stress wave evaluation of an intact concrete pile, the same pile was modelled with a defect at 2.25m from the top (1.75m below ground). The section is modelled with the radius of the pile along its depth from 2.25m to 2.50m measured from the surface was reduced from 350mm to 263mm (25% reduction) as shown in Figure 4.4. As observed from the extensive field inspection by Groundline Ltd, this defect can occur during the concreting of the pile, due to the soil wall collapsing in the trench for a bored pile. The same impulse force is applied as used for the analysis of the intact pile (Figure 4.1). Figure 4.4 shows the geometry of the defective concrete pile analysed.

Figure 4.6 shows the schematic SWP trace in the longitudinal direction for the defective concrete pile analysed. The SWP velocity was recorded at the top of the concrete pile cap from the impulse force. The purpose of the analysis is to understand the SWP patterns from a defective concrete pile and compare them to the same intact concrete pile. In Figure 4.5, Points 1, 2 and 3 will be the same as for an intact pile discussed in the previous section; initial impact, first full reflection and second full reflection from the bottom of the pile respectively. The first intermediate reflection between Points 1 and 2 will be reflection from the defect marked as Point 4 in Figure 4.5. The second and third noticeable secondary reflections from the defects are marked as Points 5 and 6. The reflections from the defects can be clearly distinguished by comparing both the intact and defective SWP velocity trace in Figure 4.7.

Based on the calculated propagation velocity 3541m/s from Table 4.1, the total length of the concrete pile would be the same as the intact pile determined as 5.85m from the impulse to the 1st reflection. The length of pile is 6.10m from the times associated with the 1st reflection and the 2nd reflection. The calculated length variation from the actual 6.0m length is due to the fixed value of time step increment. The corresponding calculated defect depth is 2.3m, 2.39m, 2.40m from the top respectively from Points 1 & 4, Points 2 & 5 and Points 3 &6. (We have already discussed that the variation will be within 0.18m.)

The reflection from the defect will be most prominent when it reflects first from the defect and then travels the full length of the pile as in the 1st, 3rd and 5th reflection in
Figure 4.5. The secondary reflections form the defects will be minor and difficult to recognise with any degree of confidence from the SWP velocity trace.

After validation of FE modelling of the SWP of an embedded concrete pile with and without defects using ANSYS 12.1, the analysis of embedded timber utility poles could then proceed with some insight of what might be expected.

Figure 4.4: Geometry of a concrete pile with a defect at 2.25m from the top

Figure 4.5: Trace points related to the SWP reflection as measured at the top of the pile
**Figure 4.6:** SWP trace of a defective concrete pile as measured at the top of the pile

**Figure 4.7:** Comparison of velocity traces as measured at the top of an intact and defective pile
4.2.3 FE Analysis of an Intact Timber Pole

The purpose of the analysis was to verify the SWP velocity pattern for an intact timber utility pole in the longitudinal direction of the pole. The FE analysis of timber utility poles for SWP in the longitudinal direction allows a similar procedure to that exercised for the concrete pile with and without defect. The differences would essentially lie in the material properties, geometry of the pole including length, diameter, tapering nature and below ground depths of the timber utility pole analysed. The material properties for the concrete are homogenous but the material properties of a timber utility pole is not homogenous (Buschow, 2001).

Timber utility poles have different properties along their radial, tangential and longitudinal directions as shown in Figure 4.8. The x and y axis are the radial direction and the z axis is the longitudinal direction in Figure 4.8. The Young’s modulus and Poisson’s ratio change depending on direction of the timber utility pole considered while the density remains the same. The longitudinal direction has the fastest SWP velocity based on these properties. The propagation in the longitudinal direction creates compressional waves along the fibre direction of the timber utility pole. The longitudinal direction SWP velocity can be calculated from Equation 3.3.

Transverse directional SWP inspection of timber utility pole is calculated based on the radial direction properties. The tangential directional SWP is not applicable with SWP inspection. The transverse directional SWP velocity is calculated from the Equation 3.4. The material properties of a timber utility pole differ from the longitudinal direction to the radial direction with the SWP velocity roughly 4-5 times lower in the radial direction than for the longitudinal direction (Buschow, 2001). This is due to the Young’s modulus in the radial direction of a timber utility pole being significantly lower than for the longitudinal direction. Further, the Poisson’s ratio is also lower for the radial direction than for longitudinal direction. Table 4.2 summarises the typical orthotropic properties of a hardwood timber utility pole extracted from Australian Standards and Encyclopaedia of materials: Science and Technology (Buschow, 2001) as used in the FE analysis.
Figure 4.9 shows the geometry for the timber pole modelled in ANSYS 12.1 and the force applied. The pole is tapered and has a diameter at the top of 250mm and at the ground line of 350mm with a total length of 15.5m. The base is fixed to a soil block and the side wall of the pole embedded in the soil block is connected with COMBIN39 coil spring elements with same properties used in the concrete pile analysis in previous sections. The embedded depth is 2.5m. The idealised impulse force as shown in Figure 4.9 was applied at the top of the pole and was the SWP velocity trace recorded on the top of the pole in longitudinal direction. The maximum 6000N impulse force is taken from field inspections of the response from timber poles with a good quality surface. The pole is embedded in a 4mx4mx6m soil block. All the faces of the soil block are fixed except for the top surface.

Figure 4.8: Principal axes of wood with respect to grain direction and growth rings
The expected SWP velocity trace is schematically shown in Figure 4.10. The velocity is recorded at the top of the timber utility pole as there is no other location to apply impulse and record the longitudinal SWP. Based on the calculated propagation velocity of 4604m/s from Table 4.2 and the ANSYS12.1 analysis time step increment of $5 \times 10^{-5}$ seconds, it is expected to have a length resolution of 0.23m ($0.00005 \times 4604$ m).

Figure 4.11 shows the SWP velocity trace for the impulse applied from the top. In Figure 4.11, the points marked as 1, 2 and 3 show the x-axis time value in seconds and Point 1 is the initial response when the impulse is applied. Points 2 and 3 are the first and second full reflections from the bottom of the pole. The total length of the pole is determined as 15.1m evaluated from the start of the impulse to the 1$^{st}$ reflection. The length of pole is 15.5m calculated from 1$^{st}$ reflection and 2$^{nd}$ reflection times. The calculated length varies from the actual length of 15.5m (13.0m above ground length + 2.5m below ground length) is due the time step increment. Nevertheless the length variation from the impulse to 1$^{st}$ reflection is 2.5% which is considered acceptable at this stage.
Table 4.2– Material properties used in the analysis of timber utility pole

<table>
<thead>
<tr>
<th>Material</th>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Timber</td>
<td>Young’s Modulus</td>
<td>E_x 1240 MPA</td>
</tr>
<tr>
<td></td>
<td></td>
<td>E_y 1240 MPA</td>
</tr>
<tr>
<td></td>
<td></td>
<td>E_z 16900 MPA</td>
</tr>
<tr>
<td></td>
<td>Shear Modulus</td>
<td>G_{xy} 6115 MPA</td>
</tr>
<tr>
<td></td>
<td></td>
<td>G_{yz} 602 MPA</td>
</tr>
<tr>
<td></td>
<td></td>
<td>G_{xz} 602 MPA</td>
</tr>
<tr>
<td></td>
<td>Poisson’s ratio</td>
<td>v_{xy} 0.30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>v_{yz} 0.03</td>
</tr>
<tr>
<td></td>
<td></td>
<td>v_{xz} 0.03</td>
</tr>
<tr>
<td></td>
<td>Calculated Velocity</td>
<td>Long 4604 m/s</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Trans 960 m/s</td>
</tr>
<tr>
<td></td>
<td>Density</td>
<td>750 kg/m³</td>
</tr>
</tbody>
</table>

Figure 4.10: Trace points related to the SWP reflection measured at the top of an intact pole
Figure 4.11: SWP velocity trace of an intact timber utility pole as measured at the top

1st return from bottom (Corresponding length = 15.1m)

2nd return from bottom (Corresponding length = 15.5m)

Full 2 cycles travel
4.2.4 FE Analysis of a Defective Timber Utility Pole

Following the successful stress wave evaluation of an intact timber utility pole in the longitudinal direction, the same pole is modelled with a defect just below ground line level. The purpose of the analysis is to check the difference between the SWP patterns from an intact timber utility pole with those from a defective timber utility pole. The defect usually happens due to weathering and deterioration around the ground line region of a timber pole and can be observed on aged timber utility poles. Mainly these defects are section reduction due to pole rotting and termite below or above ground section of the pole. In order to simulate this style of defect, the section of 0.25m length below ground is modelled as two abutting conical frusta by reducing the radius from 334mm to 250mm (25% reduction) as shown in Figure 4.12. Similar testing conditions and impulse forces are used as in the analysis of an intact timber utility pole in the previous section.

The expected SWP velocity trace is schematically shown in Figure 4.13. The velocity is recorded at the top of the timber utility pole. The 1st reflection recorded by the geophone will be from the defect. The 2nd and 4th reflections are the reflection by the SWP travelling the full length of the pole completely once and twice respectively. The 3rd reflection is from one full travel of the pole length and the up/down reflected length of the defect from the bottom of the pole length.

In Figure 4.14, the points marked as 1, 2, 3 4 and 5 show the x-axis time value in seconds. Based on the calculated propagation velocity of 4604m/s from Table 4.2 and the ANSYS12.1 analysis time step increment of 5x10^-5 seconds, it is expected to have a length resolution of 0.23m (0.00005 x 4604 m). The total length of the pole is determined as 15.1m from Points 1 and 2. The length of the pole is 15.7m calculated from Points 2 and 3. The calculated length difference from the actual length of 15.5m (13.0m above ground length + 2.5m below ground length) are comparable to the 0.25m length resolution fo the simulation process. However, the length difference from the impulse to the 1st reflection is greater than the time step resolution length (0.25m). The difference equals to a 2.5% error compared to the actual pole length and is considered to be acceptable at this stage.
In Figure 4.14, the length of the pole above the defect is 13.0m and the calculated length from Points 1 and 4 is 12.3m. Again the difference is greater than the time step resolution length (0.25m) equating to a 5% error which is also considered acceptable. The pole length calculated from Points 5 and 3 is 12.3m which is also align as the same results and conclusion. The reflections from the defects can be clearly distinguished by comparing the intact and defective trace when plotted together as in Figure 4.15.

**Figure 4.12: Geometry and the defect modelled in the timber pole analysis**

**Figure 4.13: Trace points related to the SWP reflection measured at the top of the defective pole**
The application of using SWP in the longitudinal direction for a timber utility pole is not practical due to the danger associated with accessing the pole top and the live
electricity distribution. Hence, the following sections explore the application of SWP in the transverse direction at ground level for timber utility poles.
4.3 Transverse FE Analysis

The previous section discussed details of the SWP analysis of a concrete pile and the application of SWP to a timber utility pole in the longitudinal direction with and without defects. The results for the evaluation of total length and the location of defects fairly accurate and the errors to be within the acceptable limits.

The pole and soil interface is developed here using bi-linear spring elements to model the differential displacement and restraining forces for the embedded condition. Dai et al. (2011) used linear spring elements to model the pole-soil interface during their work of assessing the embedded depth of poles. After the detailed study of understanding the soil behaviour for vibration and movement of embedded timber utility poles, it is found that the linear spring elements will not represent the reaction between the pole and soil when the pole is tested in the transverse direction. The vibration/movement of the pole surface in the compressional and tensile directions to the soil is very small typically in the range of $1 \times 10^{-6} \text{m}$. Usually, there is a small discontinuity between the pole and soil surface which is greater than the movement due to an impulse force. Further, the element should provide very limited or no resistance during the movement of the pole away from soil. In other words, the soil will not provide any tension force to the embedded pole surface. The soil should resist during compression only. The compressional resistance between the soil and timber utility poles is modelled with Dai et al.’s (2011) linear spring elements properties. The soil bearing pressure is taken as 100kPa at the process of calculating the restraining forces acting on the pole.

4.3.1 Field Transverse SWP Inspection and Validating with FE Models

The purpose of the analysis performed in this section the thesis is to investigate the transverse directional SWP velocity of an embedded, intact timber utility pole and benchmark the results from the ANSYS12.1 FE model SWP velocity results. In order to investigate the transverse directional SWP in timber poles, an in-service timber utility pole located between the Bendigo-Charlton 66kV line in Bendigo, Victoria was chosen as shown in Figure 4.16. The pole (ID 283) is 15.5m in length, of Blackbutt hardwood species, CCA treated pole with a ground line diameter of 390mm. It was installed in 2003. The pole top diameter was assumed to be 250mm based on the general tapering
nature of the pole. It was assumed that the pole has a below ground depth of 2.4m based on the minimum below ground depth criteria \((\frac{L}{6} + 0.6)\)m generally adopted by network operators in Australia.

The transverse directional impulse force was applied close to the ground line of the pole. The applied idealised impulse force and the geometry of the timber pole tested is shown in Figure 4.17. The SWP inspection was carried out by striking the pole and measuring the SWP at the same level opposite to the side where the impulse was applied. The anticipated SWP reflection pattern for a transverse directional impulse force is shown schematically in Figure 4.18. The actual field SWP velocity trace is shown in Figure 4.19.

\[\text{Figure 4.16: Field tested pole 283}\]
Figure 4.17: The length and applied idealised force details for Pole 283

Figure 4.18: Trace points related to the SWP velocity reflection measured at the point of impulse
Figure 4.19: Field SWP velocity trace for Pole 283 in the transverse direction

All the calculations are based on the SKM modified field trace. In Figure 4.19, points marked as 1, 2 and 3 show the x-axis time value in seconds. Point 1 is associated with the initial response when the impulse is applied. Point 2 is associated with the reflection of the wave travelling to the tip of the pole and returning. Point 3 is reflection of the impulse wave travelling the whole length of the pole in both directions. The reflection from the bottom of the pole marked as point 4 in Figure 4.18 cannot be identified with confidence in the SWP velocity trace shown in Figure 4.19.

The transverse direction SWP velocity of the pole is calculated from the time difference between points 1 and 3 in Figure 4.19. The total length of pole is 15.5m. The calculated propagation velocity is $997\text{m/s} \left(\frac{15.5 \times 2}{0.03175-0.00066}\right)$. The time difference between Points 2 and 3 in Figure 4.19 discloses the below ground depth of the pole. It is calculated to be $2.2\text{m} \left(\frac{(0.03175-0.02741) \times 997}{2}\right)$ based on the estimated SWP velocity (997m/s) which is lower than the actual depth of 2.4m. With a time step increment of $4 \times 10^{-5}\text{s}$ in the field trace, it is expected to have a length resolution of $0.04\text{m}(0.00004 \times 997\text{m})$. The estimated length is with an 8% error compared to the actual depth and this error is considered acceptable at this stage.
The expected orthotropic properties for Pole 283 are summarised in Table 4.3 based on a calculated field SWP velocity of 997 m/s from Figure 4.19.

<table>
<thead>
<tr>
<th>Material</th>
<th>Property</th>
<th>Value</th>
</tr>
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<tr>
<td></td>
<td></td>
<td>E&lt;sub&gt;y&lt;/sub&gt; 1550 MPA</td>
</tr>
<tr>
<td></td>
<td></td>
<td>E&lt;sub&gt;z&lt;/sub&gt; 16900 MPA</td>
</tr>
<tr>
<td></td>
<td>Shear Modulus</td>
<td>G&lt;sub&gt;xy&lt;/sub&gt; 6115 MPA</td>
</tr>
<tr>
<td></td>
<td></td>
<td>G&lt;sub&gt;yz&lt;/sub&gt; 752 MPA</td>
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<tr>
<td></td>
<td></td>
<td>G&lt;sub&gt;xz&lt;/sub&gt; 752 MPA</td>
</tr>
<tr>
<td></td>
<td>Poisson’s ratio</td>
<td>ν&lt;sub&gt;xy&lt;/sub&gt; 0.30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ν&lt;sub&gt;yz&lt;/sub&gt; 0.03</td>
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<td>ν&lt;sub&gt;xz&lt;/sub&gt; 0.03</td>
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<tr>
<td></td>
<td>Density</td>
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</tr>
</tbody>
</table>

There is a small SWP velocity difference between the field calculated velocity (997 m/s) and the FE model velocity adopted here (1001 m/s). This is because of the chosen timber material properties. The difference is found to be negligible in terms of its effects on embedment length calculations (0.4% difference in velocity).

The FE model is developed with the below ground depth of 2.4 m (required minimum) using ANSYS 12.1. Pole 283 is relatively new and assumed to have no defects. Figure 4.20 shows the SWP velocity trace from the FE model for Pole 283. The comparison of field and FE SWP velocity traces is shown in Figure 4.21.

The SKM modified field SWP velocity trace and FE simulation SWP velocity trace closely match the tip inferring close correspondence of experimentally obtained key length features of the pole with actual values.

Following the successful evaluation of transverse directional SWP for Pole 283, a timber pole with known length and condition was examined in the Powercor pole yard. The following section covers the details of the analysis and review.
Figure 4.20: FE model transverse directional SWP velocity trace for Pole 283

Figure 4.21: Comparison of field and FE model transverse directional SWP velocity traces for Pole 283
4.3.2 Pole Yard Test and FE Analysis of an Intact Pole

The purpose of this analysis is to investigate the transverse directional SWP pattern on a timber utility pole with and without defects and compare the results with those from ANSYS FE simulation. The examination was conducted in the Powercor pole yard in Bendigo, Victoria.

The pole has a diameter of 270mm at the top and 370mm at the ground line. The species of the pole tested at the yard is Blackbutt which is CCA treated to prevent termite and fungal attacks. This pole was installed in 2002 and decommissioned from service without any defects due to an upgrade with a concrete pole at that particular location.

The pole used for the test is supported at both its ends as shown in Figure 4.22. The main difference from a utility pole to the test specimen was the embedment. The applied impulse force, geophone locations and length details are shown in Figure 4.23. While the pole was supported at both ends, the impulse force was applied in the horizontal direction perpendicular to the pole axis. The geophone was kept on the opposite side of the applied impulse on the pole to reduce unwanted noise. The impulse force was applied at 2.5m from the bottom/butt of the pole in the transverse direction. The applied impulse force in the field and the idealised force used for the simulation are shown in Figure 4.24.

The expected SWP velocity trace is schematically shown in Figure 4.25. The SWP velocity is recorded from the opposite side to the applied impulse force location horizontally to the timber utility pole. Point 1 was at the impulse. The 1st reflection recorded by the geophone will be from the butt of the pole marked as Point 4. The 2nd reflection will be from the top of the pole marked as Point 2. The 3rd reflection marked as Point 3 is recorded by the geophone from waves travelling in both directions of the full length of the pole and overlapping.
Figure 4.22: Test pole arrangement at Powercor pole yard

Figure 4.23: The geometry and length details of the pole tested

Figure 4.24: The applied impulse force in field and the idealised force used for the FE simulation
Figure 4.26 shows the SWP velocity trace in the transverse direction from the 5000N impulse force applied at 2.5m from the butt for the timber utility pole. The plot shows the raw field trace and the SKM modified trace. All the velocity, length and defect calculations are based on the SKM modified SWP velocity trace. Points 1, 2 and 3 shows the x-axis time value in seconds. The calculated SWP velocity from Points 1 and 3 is $867 \text{m/s} \left(\frac{12.5 \times 2}{0.03004 - 0.00121}\right)$. The time step increment is $3.9 \times 10^{-5} \text{s}$. Hence, distance measurements have a length resolution of 0.03m ($867 \times 3.9 \times 10^{-5} \text{m}$).

- The Points 1 & 4 and Points 2 & 3 are representative of the length of the pole from the impulse to the butt. The measured physical length is 2.5m.

- The calculated length from Points 1 & 4 is 2.44m [$867 \times (0.00684 - 0.00121) / 2$]. This is within a 2.5% error or two length resolution distance of 0.03m.

- The calculated length from Points 2 & 3 is 2.54m [$867 \times (0.03004 - 0.02418) / 2$]. This is within a 1.6% error or a close to a single length resolution distance of 0.03m.

- The Points 1 & 3 will correspond to the full length of the pole. The SWP velocity was established based on these points.
Figure 4.25: Trace points related to SWP reflections

Figure 4.26: SWP velocity trace for the intact pole tested in the Powercor pole yard
Based on pole properties and the calculated SWP velocity of 867 m/s, the corresponding orthotropic material properties for the test timber utility pole as used in the ANSYS FE simulation are summarised in Table 4.4.

**Table 4.4– Orthotropic material properties used in FE analysis**

<table>
<thead>
<tr>
<th>Material</th>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Timber</td>
<td>Young’s Modulus</td>
<td>$E_x$ 1155 MPA</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$E_y$ 1155 MPA</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$E_z$ 24000 MPA</td>
</tr>
<tr>
<td></td>
<td>Shear Modulus</td>
<td>$G_{xy}$ 9230 MPA</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$G_{yz}$ 560 MPA</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$G_{xz}$ 560 MPA</td>
</tr>
<tr>
<td></td>
<td>Poisson’s ratio</td>
<td>$\nu_{xy}$ 0.30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\nu_{yz}$ 0.03</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\nu_{xz}$ 0.03</td>
</tr>
<tr>
<td></td>
<td>Calculated Velocity</td>
<td>Trans 864 m/s</td>
</tr>
<tr>
<td></td>
<td>Density</td>
<td>750 kg/m$^3$</td>
</tr>
</tbody>
</table>

Figure 4.27 shows the FE simulated SWP velocity trace of the intact pole tested at the yard. The time step increment was set as $5.0 \times 10^{-5}$ s for FE analysis. Hence, the measurement had a length tolerance of 0.04 m ($864 \times 5.0 \times 10^{-5}$ m).

In Figure 4.27, Points 1, 2 and 3 show the x-axis time values in seconds. Point 1 is the initial response when the impulse is applied. Point 2 is from the reflection from the wave travelling to the tip of the pole and returning. Point 3 is from the reflection of the wave travelling the whole length of the pole in both directions. Point 4 is from the first reflection from the bottom of the pole. Usually, Point 4 is difficult to differentiate clearly within the field trace such points they appear after the impulse with lot of variation in the SWP velocity trace. Hence, such points are mostly not taken into consideration for calculations of length. For this pole, the propagation velocity is calculated as 864 m/s based on the material properties given in Table 4.4 and Equation 3.4.
• The Points 1 & 4 will correspond to the bottom length of the pole from the location of impact. This distance is calculated as 2.46m \[864 \times (0.00645-0.00075)/2\] and has a 1.6% error and is within the length resolution of 0.04m.

• The Points 2 & 3 correspond to the bottom length of the pole from the location of impact. This length is calculated as 2.55m \[864 \times (0.03005-0.02415)/2\] and has a 2.0% error, close to the length resolution of 0.04m.

• The Points 1 & 3 correspond to the full length of the pole. The full length of the pole is calculated as 12.65m \[864 \times (0.03005-0.00075)/2\] with 1.2% which again is within the length resolution of 0.04m.

Experimental results show strong correlation to the actual bottom length of 2.5m and the total length of 12.5m of the test pole. There are no intermediate reflections because there are no defects or damage introduced to the pole. Figure 4.28 shows the comparison between the SKM modified Field and FE model SWP velocity traces.

The FE simulated SWP velocity trace and the SKM modified field traces resemble each other very closely and the key pole lengths calculated from the transverse SWP velocity are well within acceptability limits.

Hence, it is concluded that the transverse SWP is successfully simulated with ANSYS12.1 FE model and the results obtained can be used to validate and estimate key pole lengths.
Figure 4.27: FE model SWP velocity trace for intact test pole

Figure 4.28: Comparison of SKM field and FE model SWP velocity traces for an intact test pole
4.3.3 Pole Yard Test and FE Analysis of Timber Pole with above ground Defect

The previous section benchmarked the pole yard test SWP velocity results with the ANSYS 12.1 FE simulation results. To verify the effects of defects on SWP velocity trace, a defect was introduced to the same pole (used in previous section) 4m away from the tip. The pole with the defect, location and severity is shown in Figure 4.29. A 100mm deep notch was made with a chainsaw as a defect. The idealised applied impulse force, location and geometry details are shown in Figure 4.30. Similar orthotropic properties used for the intact pole, as in Table 4.4 are adapted for the analysis. The defect was modelled as a section reduction in the FE analysis.

Figure 4.29: Pole with introduced defect 4m away from tip
The anticipated SWP reflection is schematically explained in Figure 4.31. Points 1 to 4 are initial impulse, tip reflection, total reflection and anticipated bottom reflection respectively. These points are the same as for the intact pole described in the previous section. Point 5 is the first reflection from the above ground defect. Point 6 is the second reflection from the same above ground defect.

Figure 4.32 shows the SWP trace for the pole tested with a known above ground defect at the yard. Points marked as 1, 2, 3, 5 and 6 only show the x-axis value which is time in seconds. The propagation velocity is calculated to be \( \frac{12.5 \times 2}{0.02973 - 0.00095} \) approximately based on the total length of the pole between points 1 and 3. It is worth noting that the calculated SWP velocity is almost the same as the velocity of the intact pole (867 m/s). The time step increment was 3.9x10-5 s. Hence, the measurement had a length resolution of 0.03 m (869 x 3.9x10^{-5} m).

In Figure 4.31 and Figure 4.32, the time difference between Points 2 and 3 will correspond to the bottom length of the pole from the impact. The reflection from the butt is marked as Point 4. Most of the time, it is difficult to find Point 4 in a field SWP velocity trace due to noise as discussed in an earlier Section 4.3.2. Point 5 corresponds
to the first reflection from the above ground defect. Point 6 represents the secondary reflection from the same above ground defect. In addition, the time difference between Points 5 and 6 will also give the bottom length of the pole from the impact. Again, Point 6 is difficult to find in a field SWP velocity trace as the signal is damped/weak due to it involving two reflections, one from the bottom and the other as a partial reflection from the defect. The following measurements are obtained from the field investigation.

- Points 1 & 4 and Points 2 & 3 will represent the length of the pole from the impulse to the butt. The measured physical length is 2.5m.

- Points 2 & 3 also correspond to the bottom length of the pole from the location of impact (2.5m). It is calculated as 2.53m $[869 \times (0.02973 - 0.02391)/2]$ with 1.2% error so within the length resolution of 0.04m.

- Points 1 & 3 will correspond to the full length of the pole. The SWP velocity was estimated based on these points.

- Points 1 & 5 corresponds to the direct length to the defect from the location of impact (6.0m). It is calculated here as 5.80m $[869 \times (0.01430 - 0.00095)/2]$ with 3.3% error, so within five lengths of distance resolution of the test system of 0.04m.
Figure 4.31: SWP details for an impulse in the transverse direction for a pole with an above ground defect

Figure 4.32: SWP trace for a defect 4m from the tip of the test pole
The relevant FE model SWP velocity trace for the same pole with an above ground defect is shown in Figure 4.33. From the calculated propagation velocity 864m/s based on the material properties given in Table 4.4 and Equation 3.4, the following length calculations are achieved (FE model SWP velocity trace).

- Points 1 & 4 will correspond to the bottom length of the pole from the location of impact (2.5m). It is calculated here as 2.36m \[864 \times (0.00645 - 0.001)/2\] with a 5.6% error despite the length tolerance of 0.04m for the measuring system.

- Points 2 & 3 also correspond to the bottom length of the pole from the location of impact (2.5m). This length is calculated as 2.59m \[864 \times (0.03020 - 0.02420)/2\] with a 1.6% error despite the length tolerance of 0.04m for the measurements.

- Points 1 & 3 correspond to the full length of the pole (12.5m). This length is calculated as 12.61m \[864 \times (0.03020 - 0.001)/2\] with a 0.9% error despite the length tolerance of 0.04m for the measuring system.

- Points 1 & 5 correspond to the direct length of the defect from the location of impact (6.0m). It is calculated here as 6.06m \[864 \times (0.01505 - 0.001)/2\] with a 1.0% error despite the length tolerance of 0.04m for the measurement.

These experimental results represent very good correlation to the actual bottom length of 2.5m, total length of 12.5m and the 6.0m defect length on the timber utility pole using transverse directional SWP. Figure 4.34 shows the comparison of both the SKM modified Field and the FE model SWP velocity traces. Both the FE simulated the SWP velocity trace and SKM modified field traces resemble each other very closely and the lengths calculated from estimated transverse SWP velocity are well within acceptability limits. It is very encouraging that results from the tip, total reflection and reflections from defects very closely resemble the field test results and FE model. Hence, it is concluded that the transverse SWP is successfully simulated using the ANSYS12.1 FE model and the results obtained can be used to validate and estimate the pole lengths and defect locations.
It is also important to note that an above ground defect will produce a reflection between the initial impulse reflection and the tip reflection. In other words, we can observe the intermediate reflections before the tip and total reflection for an above ground defect.

Figure 4.33: FE model SWP trace for control test pole with an above ground defect

Figure 4.34: Comparison of field and FE model SWP traces for the control test pole with a defect
4.3.4 FE Analysis of Timber Pole with Above and Below Ground Defects

The previous section benchmarked the field SWP results with those from an ANSYS 12.1 FE model for a pole with above ground defect. Following the successful identification and verification of the above ground defect and its location in the previous section, the same pole FE model is tested here for a known defect 1m away from the impulse towards the butt/bottom of the pole. The defect is modelled within the same section reduction previously adopted at a 4m distance from the tip. The idealised applied impulse force, location and length details are shown in Figure 4.35. Similar orthotropic properties are adopted for the analysis as listed in Table 4.4.

![Figure 4.35: Defect locations above and below ground and impulse force details](image)

The anticipated reflection pattern/scenario is schematically described in Figure 4.36. It is noted that an above ground defect will produce a reflection between the initial impulse reflection (Point 1) and the tip reflection (Point 2). In other words, we can observe the intermediate reflections before the tip and total reflection for an above ground defect. Further, the below ground defect will create a reflection between the tip and total reflection as depicted in Figure 4.36. This will be a key aspect to observe while testing poles using SWP technology. This will assist us in identifying whether we have an above and/or below ground defect in a pole through judgement of the reflection point when looking for the tip and total reflection points.
Figure 4.36: SWP details for an impulse in the transverse direction with above above and below ground defects
The FE model SWP velocity trace from ANSYS 12.1 for the pole incorporating these above and below ground defects is shown in Figure 4.37. Points 1-6 are the initial impulse, tip reflection, total reflection anticipated bottom reflection, initial above ground defect reflection and second above ground defect reflection respectively for a pole with the same above ground defect described earlier in the previous section whereas, Point 7 is the reflection from the below ground defect.

![Figure 4.37: FE model SWP trace for the control test pole with above and below ground defects](image-url)
4.4 Field SWP Pole Testing and Confirming Results with Destructive Testing

Twenty five timber utility poles were tested in service and then tested destructively in the pole yard to verify the results obtained from the stress wave analysis. These poles were chosen by Powercor and tested as an ongoing research development with Groundline Ltd. The following section discusses results obtained from 5 poles tested in the field using SWP technology comparing these with the destructive test results. More comprehensive details of the analysis performed are presented in Appendix I.

4.4.1 Investigation of Pole No 2

Pole No. 2 is a 12.2m long, Messmate timber utility pole, installed in 1965. This pole was initially tested with our Beta Pole Tester and test data then analysed. Figure 4.38 shows the field condition of the timber utility pole inspected using the Beta Pole Tester.

The SWP velocity for this pole is 997m/s computed from the reflections and pole total length (12.2m). The estimated below ground depth from tip and total reflection is 2.35m. Further, there is an intermediate reflection found between the tip and the total reflection as shown in Figure 4.39. Therefore, it is interpreted based on the transverse SWP velocity as a below ground defect at 1.05m from the ground level. At this stage of the research, any defect is alleged to be a section reduction. In Figure 4.39, the green line is
the field trace and the blue line is the conceptual simulation representing the start, total and tip reflections with any relevant reflection for defects.

The SWP analysis result is closely benchmarked with the destructive testing as shown in Figure 4.40.

Figure 4.39: The SWP inspection results of Pole No.2

Figure 4.40: The destructive test of Pole No.2
4.4.2 Investigation of Pole No 18

Pole No. 18 is a 10.5m long, Messmate timber utility pole, installed in 1965. This pole was tested with the Beta Pole Tester and analysed. Figure 4.41 shows the field condition of the timber utility pole inspected using the Beta Pole Tester.

![Field inspection condition of Pole No.18](image)

The SWP velocity for this pole is 1177m/s computed from the reflections and total length of 10.5m. Further, there is an intermediate reflection found between the tip and the total reflection as shown in Figure 4.42. Hence, it is calculated based on the transverse SWP velocity as a below ground defect at 1.46m from the ground level. There are multiple reflections between the start and tip reflections. This is an indication of the presence of multiple defects above the ground section of the pole so it becomes difficult to calculate the defect location. In Figure 4.42, the green line is the field trace and the blue line is the conceptual simulation representing the start, total and tip reflections with any relevant reflection for defects.

The SWP analysed result is closely benchmarked with the destructive testing result as shown in Figure 4.43. There is termite infestation through the pole right up to the tip from the ground level. It is observed in Figure 4.43 that the ground line section was almost intact as the pole was treated for termite (pole savers used). It is presumed that,
there is section reduction below ground starting at 1.5m and multiple locations with section reduction above ground of the pole.

Figure 4.42: SWP inspection results of Pole No.18

Figure 4.43: Destructive test of Pole No.18
4.4.3 Detailed Investigation of Pole No 392

Pole No. 392 is a 14m long, Southern Mahogany timber utility pole, installed in 1977. This pole was tested with our Beta Pole Tester and analysed. Figure 4.44 shows the field condition of the timber utility pole inspected using the Beta Pole Tester.

![Field inspection condition of Pole No.392](image)

The SWP velocity for this pole is 1459m/s computed from the reflections and total length of 14m. The estimated below ground depth from tip and total reflection is 2.22m. There are intermediate reflections found before the tip reflection as shown in Figure 4.45. The return reflection is very damped in amplitude. On the other hand, the impulse force input is good but the pole damped the SWP signal. This indicates that the pole has very limited hardwood or solid timber. There is a strong reflection before the tip which corresponds to the transformer fixed about the mid height of the pole. From the analysis, the height is estimated to be 6.5m from ground. In Figure 4.45, the green line is the field trace and the blue line is the conceptual simulation representing the start, total and tip reflections with any relevant reflection for defects.

The SWP analysis results are closely benchmarked with the destructive testing as shown in Figure 4.46. There is termite infestation through the pole right up to the tip. The ground line section was almost intact as this section has been treated for termites. There are significant section reductions below and above ground of the pole.
Figure 4.45: SWP inspection results of Pole No.392

Figure 4.46: Destructive test of Pole No.392
4.4.4 Detailed Investigation of Pole No 76

Pole No. 76 is a 10.5m long, Messmate timber utility pole, installed in 1965. This pole was tested with our Beta Pole Tester and subsequently analysed. Figure 4.47 shows the field condition of the timber utility pole inspected using Beta Pole Tester.

![Field inspection condition of Pole No.76](image)

The SWP velocity for this pole is 859m/s computed from the impulse, total reflection and total length of 10.5m. The estimated below ground depth from the tip and total reflection is 2.31m. This pole was tested 2m above ground level due to the water level. There are intermediate reflections found before the tip reflection as shown in Figure 4.48. There is a possible below ground reflection which is seen between the tip and total reflection. The intermediate reflections could be due to the applied impulse force being 2m above the ground which created the pole to vibrate locally. In any case, the applied impulse force over time frame is satisfactory. This indicates that the pole has sound hardwood around the location the applied of impulse force. In Figure 4.48, the green line is the field trace and the blue line is the conceptual simulation representing the start, total and tip reflections with any relevant reflection for defects.

The destructive testing showed no above ground defects but the pole disintegrated below the ground level as shown in Figure 4.49.
Figure 4.48: SWP inspection results of Pole No.76

Figure 4.49: Destructive test of Pole No.76
4.4.5 Detailed Investigation of Pole No 77

Pole No. 77 is a 10.5m long, Messmate timber utility pole, installed in 1965. This pole was tested with the Beta Pole Tester and analysed. Figure 4.50 shows the field condition of the timber utility pole inspected using the Beta Pole Tester.

![Field inspection condition of Pole No.77](image)

The SWP velocity for this pole is 926m/s computed from the impulse, total reflection and total length of 10.5m. This pole was tested 2m above ground due to the ground conditions being wet with water. The calculated below ground depth from the tip and total reflection is 2.19m (4.19m-2.0m). There are no intermediate reflections either before the tip reflection or between the tip and total reflection as shown in Figure 4.51. The impulse force is very high over a short duration. This indicates the good hardness of the pole around the inspection point. In Figure 4.51, the green line is the field trace and the blue line is the conceptual simulation representing the start, tip and total reflections.

From the transverse SWP analysis, this pole appeared to be in good health and to be free of defects. This result is further validated from the destructive testing results shown in Figure 4.52.
Figure 4.51: SWP inspection results of Pole No.77

Figure 4.52: Destructive test of Pole No.77
4.5 Stress Wave Propagation Summary and Conclusion

This chapter explains in some detail the various aspects of SWP in the longitudinal and transverse directions. The longitudinal direction SWP inspection approach for the integrity testing of concrete piles is a very common technique all around the world. The longitudinal direction SWP can also be applied to timber utility poles. However, the application of the impulse force and recording the SWP trace for an embedded timber utility pole will need to be at the top of the pole. This results in a tedious procedure because of the access the top of a pole and the associated risks of possible electrocution being close to live transmission wires. Further, accessing the top of the pole would require additional mechanical and human resources with a very high cost while prolonging the inspection time.

The transverse direction SWP velocity is found to be lower than the longitudinal SWP velocity for timber utility poles because of the orthotropic properties of timber. The transverse directional SWP inspection techniques is quiet practical and expedient for inspection of an embedded timber utility pole. An embedded timber utility pole with an above ground defect will indicate an intermediate reflection point before that for the tip reflection when tested in the transverse direction with an impact force close to the ground line. In addition, the same pole will indicate an intermediate reflection point between that for the tip and total reflection if the pole has a below ground defect.

The SWP traces from the control tests and FE models closely matched clearly verifying the expected relationship. The expected reflections from defects above the ground, below the ground and both acting together gave promising results for this method as was to be expected.

As discussed throughout this chapter, when there is an above ground defect, there will be a strong reflection between the start and tip reflections of a pole under test. It is relatively easier to identify the first reflection from the above ground defect using this testing technique. However, there will also be a second reflection from the above ground defect between the first defect reflection and tip reflection. It is found from the FE model simulation, there will be a noticeable secondary reflection for an above ground defect when the defect is severe. When the defect is relatively small, it is difficult to identify this second reflection point for the above ground defect.
At this stage, there is no research undertaken to verify the severity of the damage detected. It appears that there has to be a significant discontinuity in the timber pole for the reflection in the velocity trace to be picked up. The type of failures and defects that this approach can identify may be limited to cracks, significant gaps in the transverse direction of the pole. It will be hard to identify splits and cracks along the length of the pole using the SWP technology. Further, additional research work is presented in Section 6.6 discussing the defect severity to be picked up by this technology.

Hence, we can only confirm that an above ground defect exists when if there is any intermediate reflection between tip and start reflections when the cracks or discontinuities are large. On the other hand, when there is a below ground defect, we can locate the reflection for a below ground defect between the tip and total reflections. This is point where we need pay close attention to identify the tip and total reflection points so we can estimate the SWP velocity of the timber utility pole. A user can simply misjudge a below ground defect reflection to be a tip reflection or a total reflection point. (The process of selecting the Reflection points was discussed in detail in Section 5.2.)

When a timber utility pole has multiple above and below ground defects, there would be multiple reflections. This will create a situation where the evaluation of the SWP velocity become trace very complicated or impossible identification of for the reflections. Hence, this presence as a limitation of this technique. In any case, poles that exhibits such identification difficulties can be still categorised as having multiple defects above the ground. This situation is common for the NDT evaluation of concrete piles using the SWP. In the piling industry, it is not possible to identify a pile with multiple defects along the pile shaft. Consequently, this technique can be claimed to be effective in picking and confirming the presence of a single defect above and/or below the ground line of the pole.

This technology is promisingly picking up the below ground depths, defects above and below the ground and both. Hence, it was decided to trial the technology in the field and collect SWP velocity data for further analysis. This will help to investigate the sensitivity, accuracy and any limitations of this SWP technique in pole testing applications. From there, the research will focus on developing the algorithms for easy identification of defects for the field assessments of timber utility poles.
The applicability of the Beta Pole Tester to detect defects and damage was examined by testing timber utility poles with Powercor around the Bendigo region. The poles tested with the transverse SWP technology were then destructively tested to confirm the analysis results obtained using the Beta Pole Tester. The outcome from the destructive testing of the timber utility poles at the Powercor pole yard has vouched the transverse SWP results obtained from the Beta Pole Tester. However, the sensitivity for detecting defects, the severity of the defects detected and the remaining service life of a timber utility pole are unable to be predicted at this stage of the research. Further field data and controlled tests are needed to investigate these properties.

The following chapter discusses the field application and its outcomes of the SWP inspection technique in transverse direction when applied to timber utility poles.
Chapter 5. **FIELD TESTING AND HEALTH ASSESSMENT OF TIMBER UTILITY POLES**

### 5.1 Introduction

The previous chapter successfully demonstrated the capability of the Beta Pole Tester for non-destructive inspection of embedded timber utility poles. The promising controlled and field test results unlocked the opportunity to use the Beta Pole Tester for a large trial in New Zealand. In this trial, the Beta Pole Tester was used by a pole inspection crew as an additional tool to what they currently perform. This trial was carried out to examine the limitation of the Pole Tester and potentially benchmark its results with current inspection process. In NZ, the current inspection process is simply based on visual and sounding with a scoring system used to assess the condition of the pole. This scoring system mainly focuses on the age, type, ground line diameter, lean, visual defects, location and attached utilities.

In this chapter, the results from the Beta Pole Tester for approximately 600 timber poles are presented collected by the author in New Zealand working in conjunction with Groundline Engineering. The inspections were performed on different types of poles with and without defects to identify the limitations and to tweak the Beta Pole Tester. The results are critically analysed to verify the effects of different parameters such as pole species, age, height and diameter. The detailed study of this field test is presented in this chapter. The following section explains the process of analysing the SWP trace in time domain to find out the SWP velocity.
5.2 Detailed Approach to Transverse SWP Velocity Trace Analysis.

As discussed in the previous section, the typical pole propagation velocity is the key parameter to start a SWP velocity trace analysis. The total length of the pole can be found from the pole disc information. In Australia, the below ground depth of a timber utility pole should not be less than \( \frac{L}{9} + 0.6 \) m. In New Zealand, the minimum below ground depth of a timber utility pole should be not less than \( \frac{L}{6} + 0.3 \) m where in both cases \( L \) is the total length of the pole in metres.

The identification of Start, Total, and Tip reflections and establishing the pole SWP velocity are the steps involved in the time domain analysis of a timber utility pole. Later the user can look for any unusual features on the reflections and correlate them to defects in the pole based on the transverse SWP velocity of the pole. The steps involved in the calculation process are as follows;

Step 1. For example, take the transverse SWP velocity trace shown in Figure 5.1. This is for timber utility pole P421259. This is a 9m, softwood pole installed in 1997. From Table 5.1, the average transverse SWP velocity is 1200m/s with a \( \pm 115 \) m/s standard deviation, approximately. The initial start time of the SWP is at 0.98ms marked as Point 1 in Figure 5.1.

Step 2. For the total reflection, the transverse SWP velocity window will be based on \( 1085 \text{m/s} - 1315 \text{m/s} \) (1200\( \pm \)115). The total reflection point should with the addition of the initial start time, lie between \( (9 \times 2)/1315 \text{ s} - (9 \times 2)/1085 \text{ s} \). That is between 14.67ms-17.57ms which is marked in the plot as lying between Line A and Line B.

Step 3. From the above window the total reflection point is found to be at 16.33ms which is marked as Point 2 in Figure 5.1. Now, we can redefine the exact transverse SWP velocity from the total length and the total travel time. The transverse SWP velocity will be \( (9 \times 2)/(0.01633-0.00098) \text{ m/s} \), that is 1173m/s.

Step 4. Now we can find out the tip reflection which is marked in Figure 5.1 as Point 3. The time based length different between the tip and total reflection (Points
2 & 3) will give the pole below ground depth. The minimum pole below ground depth is \((\frac{L}{3} + 0.6)m = 1.60 \text{ m}\) where \(L\) is the total pole length. The calculated actual below ground depth is \(1173 \times (0.01633 - 0.01340)/2 = 1.72 \text{ m}\)

Step 5. If there are any significant intermediate reflection points between Points 1 & 3 these will represent any above ground defects on the pole. Any reflection between Points 2 & 3 would be associated with below ground defects. For this example, there are no significant intermediate reflection between Points 1 & 3 and Points 2 & 3. (These aspects are explained in Section 4.3.)

![Figure 5.1: Field transverse SWP velocity trace for Pole P421259](image)

### 5.3 Christchurch Pole Testing and Results

The 600 timber utility pole results collected from Christchurch were individually analysed. These results are reviewed critically and presented in this chapter. The detailed summary of all 600 pole results is attached in Appendix H. From each transverse SWP observation, the transverse propagation velocity is estimated as explained in Section 4.3.2. From the estimated propagation velocity, the embedment depth and possible defect locations are calculated. The transverse SWP inspection is carried out as close as possible to the ground level. This is to keep the calculation of
below ground pole depth and possible defect locations fixed for every test. The collected data is analysed to see the effects on transverse SWP velocity for different age, height, diameter and species of timber utility poles. The following section explains the process of analysing the SWP trace in time domain to find out the SWP velocity.

5.3.1 Effects of Pole Age, Height and Diameter with SWP Velocity

As we have already discussed in section 2.2, the aging of timber utility poles can change the properties of the material. A timber utility pole is normally expected to be in service for around 40-50 years without failure from natural deterioration. The transverse SWP velocity is determined from the material properties of the timber utility pole as explained in Equation 3.4. Hence, it is important to investigate the change of SWP velocity within the service life period of a utility pole. Figure 5.2 shows a plot of the transverse SWP velocity against the installation year regardless of the pole species, height and diameter. From Figure 5.2, it is clear that there is no significant change in transverse SWP velocity based on the year of installation. The SWP velocity is considered to be the same as the material properties of an in-service timber pole does not vary too much to make a significant big difference in the SWP velocity. Further, the detailed analysis considering the year of installation and height for different species of the poles is shown in Table 5.1 for both softwood and hardwood. The results substantiate those from Figure 5.2. This simplifies the inspection process to one of setting a band in the time domain of the velocity trace to identify the total reflection of the timber utility pole inspected using transverse SWP technology. This is explained in detail in Section 5.2. The normalised SWP velocity for both softwood (SW) and hardwood (HW) is given in Figure 5.3 and Figure 5.4.
A timber utility pole is expected to have the same transverse SWP velocity regardless of the height or the diameter of the pole for the same species. The transverse SWP velocity is related only to the material properties of the pole as explained in Equation 3.15. This phenomenon is substantiated from Figure 5.5 which shows that the length of the pole has insignificant effect on the transverse SWP velocity of a timber utility pole. This is clearly shown in Table 5.2. Figure 5.6 shows that there is no remarkable change in SWP velocity against the change of the diameter of a timber utility pole, where the diameter of the pole is measured at ground level. Table 5.3 shows that there is no
relationship between the height and diameter of the pole to the transverse SWP velocity. Hence, the transverse SWP inspection will not be affected by the length or diameter of a timber utility pole.

Figure 5.3: Normalised distribution of SWP velocity for SW poles

Figure 5.4: Normalised distribution of SWP velocity for HW poles
Figure 5.5: Effect of pole length on propagation velocity

Table 5.2– Details of SWP velocity for different diameter vs. age.

<table>
<thead>
<tr>
<th></th>
<th></th>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SW</td>
<td>HW</td>
<td>SW</td>
<td>SW</td>
</tr>
<tr>
<td></td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
<td>SD</td>
</tr>
<tr>
<td>All Diameter</td>
<td>1205 (54)</td>
<td>113</td>
<td>1173 (129)</td>
<td>109</td>
</tr>
<tr>
<td>100-150</td>
<td>1182 (19)</td>
<td>131</td>
<td>1157 (54)</td>
<td>113</td>
</tr>
<tr>
<td>151-200</td>
<td>1219 (29)</td>
<td>106</td>
<td>1184 (56)</td>
<td>106</td>
</tr>
<tr>
<td>201-250</td>
<td>1213 (6)</td>
<td>88</td>
<td>1170 (14)</td>
<td>121</td>
</tr>
<tr>
<td>250 &amp; above</td>
<td>1184 (12)</td>
<td>117</td>
<td>1151 (5)</td>
<td>66</td>
</tr>
</tbody>
</table>

*Number within brackets indicates the number of poles with the data analysis

Table 5.3– Details of SWP velocity for different diameter vs. height.

<table>
<thead>
<tr>
<th>Pole Diameter</th>
<th>Velocity in m/s</th>
<th>Height &lt; 9.0m</th>
<th>9.0m ≤ Height &lt;10.0m</th>
<th>Height &gt; 10m</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SW</td>
<td>HW</td>
<td>SW</td>
<td>SW</td>
</tr>
<tr>
<td></td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
<td>SD</td>
</tr>
<tr>
<td>All Diameter</td>
<td>1191 (69)</td>
<td>120</td>
<td>1148 (59)</td>
<td>106</td>
</tr>
<tr>
<td>100-150</td>
<td>1195 (23)</td>
<td>116</td>
<td>1141 (22)</td>
<td>105</td>
</tr>
<tr>
<td>151-200</td>
<td>1190 (34)</td>
<td>34</td>
<td>1145 (29)</td>
<td>117</td>
</tr>
<tr>
<td>201-250</td>
<td>1184 (12)</td>
<td>117</td>
<td>1151 (5)</td>
<td>66</td>
</tr>
</tbody>
</table>

*Number within brackets indicates the number of poles with the data analysis
Figure 5.6: Effect of pole diameter on propagation velocity
5.4 Health Assessment of Timber Utility Poles

Health assessment of timber utility poles can be performed in two stages. The first assessment of timber utility poles is from the infield test. Later, further analysis is performed from the investigation of its SWP trace. In field health assessment of timber utility poles is mainly performed from the field parameters impulse force and force duration. It is important to apply a good impulse force to the timber utility pole to get a meaningful SWP velocity trace. There should be sufficient energy input into the pole to get the transverse directional SWP to travel through the full length of the pole. Material damping will attenuate the SWP. If the impulse energy transferred into the system is insufficient, the returning stress waves are more likely to be dampened out. This will result in no further SWP analysis on the trace. Hence, it is very important to monitor the impulse force and impulse duration during the inspection and rectify the situation when needed.

When the applied impulse is insufficient or improper, the inspection has to be repeated. Figure 5.7 shows the impulse force vs. force duration for all collected hardwood and softwood poles in Christchurch. This data is further investigated for different ages of the poles as shown in Figures 5.8 to 5.10 for the period pre 1975, 1975-1990 and after 1990 respectively. This age group parameter is like a hardness test of the material. Here, investigation is restricted to the location of the impulse applied. A high impulse force within a short duration, as shown in Figure 5.11, indicates very high hardness of the pole while a low impulse force over a long duration indicates a soft surface as shown in Figure 5.12. These results are analysed as Normal distribution plots as shown in Figure 5.13 and Figure 5.14. This investigation provides us with critical information to set the hardness boundaries and to decide whether the impulse has transferred sufficient energy into the pole to investigate with SWP technology. Based on the values derived from the normalised plots, Figure 5.15 and Figure 5.16 depict the conceptual zones for impulse force categorisation over the duration.
Figure 5.7: Impulse force against duration

Figure 5.8: Impulse force against duration (Poles before 1975)
Figure 5.9: Impulse force against duration (Poles between 1975-1990)

Figure 5.10: Impulse force against duration (Poles after 1990)
CHAPTER 5  FIELD TESTING AND HEALTH ASSESSMENT OF TIMBER UTILITY POLES

Figure 5.11: Temporal and spectral impulse force on a hard pole surface

Figure 5.12: Temporal and spectral impulse force on a soft pole surface

Figure 5.13: Normalised plot for impulse force
Figure 5.14: Normalised plot for impulse force duration

Figure 5.15: Screening of impulse force and duration for 95% distribution
Figure 5.16: Screening of impulse force and duration for 97.5% distribution
5.5 Field Testing Conclusion

This chapter discussed in detail the field application of the Beta Pole Tester. The pole tester is designed to collect pole data over a whole day with one charge of the unit. The unit collects the SWP traces along with the GPS location of the pole to match the details from the network provider’s electricity distribution map. The screening system for applied impulse force to the timber utility pole shown in Figure 5.15 and Figure 5.16 has been ascertained mainly from the collected field data in Christchurch. The results can be further investigated and improved by collecting and analysing more on the pole SWP data collected. There is no correlation between a timber utility pole’s age, height, diameter and species to the SWP velocity. This is empirically derived by analysing the collected Christchurch pole data.

From the field analysis, the initial average SWP velocity to start the investigation of a timber utility pole is found to be 1200m/s with a standard deviation of about ± 110m/s. This will set a region to look for the total reflection of a pole based on the total length of the pole. After picking the total reflection point, the actual SWP velocity of a timber utility pole can then be established. This will unlock all the other pole related aspects to be calculated based on the calculated SWP velocity.

The following chapter discusses the parameters that influence the transverse SWP technology for inspecting timber utility poles. Parameters such as age, height, diameter, taped nature, species of timber, applied impulse force, the location of inspection, the sensitivity of the technique in picking defects and the severity of the defects are critically reviewed.
Chapter 6.  PARAMETRIC STUDY OF TIMBER UTILITY POLES USING FE ANALYSIS

The previous chapter demonstrated the successful application of transverse SWP technology for investigating possible damage in timber utility poles. The Beta Pole Tester using transverse SWP technology delivers the length details and detects the presence of defects above and/or below the ground of an embedded timber utility pole. The transverse SWP velocity is initially estimated to range between 1200m/s ±115m/s from the preliminary data collected from Christchurch pole tests in Section 5. The velocity data determined from Christchurch may be only suitable for poles located in and around Christchurch. The transverse SWP velocity for different locations can be determined from gathering more pole data especially from the locations of interest in applying its technique. The critical analysis of the pole transverse SWP velocity against the height, diameter, age and species of utility poles proves the velocity is largely independent of these parameters. The impulse data (Impulse force against force duration) can be used to ensure the transfer of sufficient energy into the timber pole. It also reveals the relative hardness of the pole at the location of the impulse.

It is also very important to verify the effects of the parameters such as pole height, diameter, tapering nature, applied impulse force, applied force location, defect locations and severity over the transverse SWP velocity. This chapter discusses the effects of these parameters with the aid of FE models using ANSYS 12.1. A basic 15.5m long timber utility pole with a 350mm ground line diameter and 250mm top diameter is analysed with a typical 4000N impulse force. The properties of the pole used for the FE analysis are given in Table 6.1.

It is worth noting before we move on to the detailed analysis, parameter adopted for the time step and other parameters considered in the FE analysis using ANSYS 12.1. The time step increment is set as $5 \times 10^{-5}$s. The typical 15.5m timber utility pole (decided to
be analysed with a 2.5m below ground depth) is considered with a transverse SWP velocity of 945m/s for the set of material properties depicted in Table 6.1. This means that the total SWP travel time will be around 0.03280s for this timber pole FE model. With the $5 \times 10^{-5}$s time step increment, the velocity can vary between 943.6m/s-946.6m/s due to the time step resolution. Further, when choosing the reflection point peaks, much attention should be paid to get the correct time line value on the plot.

Table 6.1–Material properties used for parametric study of example timber pole

<table>
<thead>
<tr>
<th>Material</th>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Timber</td>
<td>Young’s Modulus</td>
<td>$E_x$ 1380 MPa</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$E_y$ 1380 MPa</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$E_z$ 16900 MPa</td>
</tr>
<tr>
<td></td>
<td>Shear Modulus</td>
<td>$G_{xy}$ 6115 MPa</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$G_{yz}$ 670 MPa</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$G_{xz}$ 670 MPa</td>
</tr>
<tr>
<td></td>
<td>Poisson’s ratio</td>
<td>$\nu_{xy}$ 0.30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\nu_{yz}$ 0.03</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\nu_{xz}$ 0.03</td>
</tr>
<tr>
<td></td>
<td>Calculated Velocity</td>
<td>Trans 945 m/s</td>
</tr>
<tr>
<td></td>
<td>Density</td>
<td>750 kg/m³</td>
</tr>
<tr>
<td>Soil</td>
<td>Young’s Modulus</td>
<td>400 MPa</td>
</tr>
<tr>
<td></td>
<td>Density</td>
<td>1800 kg/m³</td>
</tr>
<tr>
<td></td>
<td>Poisson ratio</td>
<td>0.45</td>
</tr>
</tbody>
</table>
6.1 Height of Pole

The first objective of the analysis is to verify the effects of different heights of a timber pole with similar properties over the transverse SWP velocity. It is found in the previous chapter, that the heights have insignificant effects on the transverse SWP velocity. There are three pole FE models generated here with ANSYS 12.1 and analysed to verify the SPW velocity. These poles are 9.5m, 12.5m and 15.5m in length with the same properties as given Table 6.1 and with the same 2.5m below ground depth.

Figure 6.1 shows the transverse SWP velocity for the 9.5m, 12.5m and 15.5m long FE pole models. The traces are separated in the Y axis by changing the base line of 9.5m and 15.5m pole velocity data. Time data is fixed for all three traces in the X axis. The propagation velocities for each model are calculated according to section 5.2. The transverse SWP velocities are 940.6m/s, 941.6m/s and 940.8m/s for pole heights of 9.5m, 12.5m and 15.5m respectively. This satisfies the conclusion arrived in the previous section that the pole velocity does not depend on the pole height.

![Figure 6.1: SWP velocity trace for poles with different height](image)

Figure 6.1: SWP velocity trace for poles with different height
6.2 Diameter of Pole

The nature of this analysis is to verify the effects of different diameter of timber poles with similar properties over the transverse SWP velocity. It should be noted that it is concluded in the previous chapter, that the diameter has no effect on the transverse SWP velocity. Three pole FE models are generated with ANSYS 12.1 and analysed to verify the SPW velocity. These poles are off the same height of 15.5m with the same properties as given in Table 6.1 but with different ground line diameters of 250mm, 350mm and 450mm respectively. The tapering ratio of the pole is kept to be the same at about 1/300

Figure 6.2 shows the transverse SWP velocities for the 250mm, 350mm and 450mm ground line diameter FE pole models. The traces are separated in the Y axis by changing the base line of 250mm and 450mm diameter pole velocity data. Time data is fixed for all three traces in the X axis. The calculated transverse SWP velocities for each model are 955.3m/s, 943.6m/s and 948.0m/s for pole diameters of 250mm, 350mm and 450mm respectively. This again satisfies the conclusion arrived in the previous section that the pole velocity does not depend on the pole diameter.

![Figure 6.2: SWP velocity trace for poles with different diameters](image)

163
6.3 Tapering Nature of Pole

The objective of this analysis is to verify the effects of different tapering of timber poles with similar properties over the transverse SWP velocity. The previous chapter did not consider possible pole tapering effects upon the analysis due to the unavailability of data. In any case this parameter is assumed to have no significant effect on the transverse SWP velocity of a timber pole. There are three FE pole models generated with ANSYS 12.1 and analysed to verify the SWP velocity is not influenced by the typical tapering conditions in timber poles. The poles in these models of the same height of 15.5m with the same properties as given in Table 6.1 but with different tapering of 350mm-250mm, 350mm-300mm and 350mm-350mm (no taper).

Figure 6.3 shows the transverse SWP velocity for different tapering properties of the pole. The traces are separated in the Y axis by changing the base line. Time data is fixed for all three traces in the X axis. The calculated transverse SWP velocities are 942.2 m/s, 936.6 m/s and 946.6 m/s for pole tapering of 350mm-250mm, 350mm-300mm and 350mm (no tapering) respectively. This validates the results in Section 5.3 SWP velocity prediction with negligible change in pole transverse SWP velocity for different tapering features in timber poles.

![Figure 6.3: SWP velocity trace for poles with different diameters](image)

Figure 6.3: SWP velocity trace for poles with different diameters
6.4 Different Impulse Forces

The impulse force applied to the timber utility pole is an important parameter to be identified to get a decent transverse SWP velocity trace. The previous chapter discussed in detail the impulse data for the collected poles in Christchurch. From the field results, it is found that the minimum impulse needed to produce reliable SWP velocity traces to be approximately 2000N minimum. There are three different impulse force applied to the same FE pole model and generated transverse SWP traces using ANSYS 12.1. The pole is 15.5m height with same properties as given in Table 6.1 but applied with different impulse forces of 500N, 2000N and 4000N.

Figure 6.4 shows the transverse SWP velocities for different applied impulse forces. The traces are separated in the Y axis by changing the base line. Time data is fixed for all three traces in the X axis. The calculated transverse SWP velocities are 943.6m/s and 940.8 for applied impulses of 2000N and 4000N respectively. For the applied impulse force of 500N, the trace is highly damped and it is very difficult to read or estimate the propagation velocity. This phenomenon validates the detailed analysis of impulse force over duration obtained from the field testing in Christchurch.

Figure 6.4: SWP velocity trace for poles with different impulse force values
6.5 Location of Impulse Force

The impulse force applied is as close to the ground level as possible. This is to eliminate any confusion with the estimation of below and above ground lengths and defect locations. However, in particular cases, it is worthwhile to repeat the inspection test using impact in different locations above the ground. Chapter 4 discussed in detail identifying defect locations from the position of reflections within the trace that can indicate associated above or below ground defects. When it is suspected there to be a below ground defect, the associated reflection will appear between the tip and total reflections. On the other hand, if the defect is above ground, the reflection for the defect will appear between the start and tip reflection positions. These are the aspects to consider when redefining the location of the impulse to confirm the existence and location of a defect. Three different locations for the application of impulse force are chosen on same FE pole model and generated transverse SWP traces using ANSYS 12.1. The pole is of 15.5m height with the same properties as given in Table 6.1 but where the applied impulse force is varied to be at the ground line, 1m and 2m above ground. A typical comfortable maximum height an inspector could reach to conduct the test would be 2m from ground level.

Figure 6.5 shows the transverse SWP velocities for applied impulse forces at different locations identified as the ground line (marked as Force @ 2.5m), 1m above ground (marked as Force @ 3.5m) and 2m above ground (marked as Force @ 4.5m). The traces are separated in the Y axis by changing the base line. Time data is fixed for all three traces in the X axis. The calculated transverse SWP velocities are 942.2m/s, 939.4m/s and 940.8 m/s for the applied impulse location of at the ground line, 1m and 2m above ground level further respectively. It is clear from the Figure 6.5, that the tip and total reflection are much apart when the impulse is applied above the ground level. Hence the below ground defect reflection appears between the tip and total reflection, and the calculation of defect location will be less complicated and more accurate when we apply the impulse above ground.

In addition, the location of impulse will affect locating defects in the pole. Locating the defects rely on picking the intermediate reflections/response from the defects in addition to the normal expected responses from initial hit, potential below ground length, tip and...
total length of the pole. From Figure 6.5, if there is a defect just below or above ground level (ground level marked at 2.5m), it is impossible to pick up from the inspection applied at 2.5m mark. It is possible to pick the defect from inspections at 3.5m & 4.5m locations. It is found from the analysis and field trial, that this technique will not identify defects when a defect is within 0.5m above or below from the inspection location.

![Figure 6.5: SWP velocity trace for poles with different impulse location](image)

*Figure 6.5: SWP velocity trace for poles with different impulse location*
6.6 Defect Severity

The previous section discussed the importance of changing the location of the impulse force when a timber utility pole is suspected to have a below ground defect. This will keep the reflection from the defect isolated from the tip and total reflection. This section of parametric study investigates the severity of defects that could be detected by the inspection technology. The sensitivity for severity of defects with this technique has not been investigated in the field using controlled tests of timber utility poles. This therefore remains as an important aspect to be investigated.

There are three FE pole models developed with a below ground defect for this investigation. There is a defect in the pole starting at 0.5m below ground level for a length of 0.3m. This defect is idealised to a section reduction from outside to inside diameter of the pole. These section reductions are modeled in three stages of 20%, 30% and 40% of the diameter of the pole. All the other material properties are according to Table 6.1. The pole is 15.5m in length and having a ground line and tip diameter of 350mm and 250mm respectively. The impulse force is applied at 2.0m above ground level as discussed in the previous section. Figure 6.6 shows the transverse SWP traces obtained from the FE analysis.

![Figure 6.6: SWP velocity trace for poles with different defect severity](image)

---

*Figure 6.6: SWP velocity trace for poles with different defect severity*
The transverse SWP velocity for the FE models are 938.0m/s, 935.1m/s and 933.7m/s for the pole with a diameter reduction of 20%, 30% and 40% respectively in modelling the below ground defect. The distance between the tip and total reflection points should give the total below ground depth plus 2.0m above ground height where the impulse is applied. The defect location is calculated at 2.0m+0.45m below the point of impulse for the transverse SWP trace with a 40% diameter reduction defect for the point marked as ‘D’.

At this stage of the study, the technology appears to pick the existence and location with confidence when the severity reaches about 40%. The defect usually happens due to weathering and deterioration around the ground line region of a timber pole and can be observed on aged timber utility poles. Mainly these defects are mainly section reduction of the pole due to pole rotting and termite below or above ground section of the pole. Defects such as cracks or splits in the longitudinal direction of the pole and knots have not been studied at this stage of the research. This could be possibly further improved with additional field testing and fine adjustment of the properties of the timber pole model. Whilst it may still be possible to pick up damage level may be equivalent to a lesser than 40% reduction in the pole diameter, at this stage we are not prepared to pinpoint the maximum damage severity that can be confidently identified by transverse SWP inspection.
6.7 Parametric Study Conclusion

The parametric study of timber utility poles highlights factors that affect the analysis for the transverse SWP inspection technology. Some of the conclusions concerning these parameters have already been derived empirically from the field testing data collected in Christchurch. This is discussed in the previous chapter.

Typically poles with heights 8.0m – 15.5m were considered in the review for the effects of heights on SWP velocity. It is found that the different heights will have no change on the SWP velocity. Similarly, the diameter and the tapering nature of the pole do not have any effect on the SWP velocity.

The applied impulse force is critical with getting the SWP throughout the full length of the pole. From the analysis, it is found that any impulse force less 500N is not sufficient to transfer the SWP over the full length of a typical timber pole. The impulse force around 4000N is ideal which will clearly show the responses of the pole lengths.

It is found that the change in location of the impulse force from the ground line to above ground level will be beneficial in differentiating the reflections from the below ground defects to the tip and total reflection. Defects within 0.5m above or below from the SWP impulse/inspection location is not possible to detect using this technology.

At this stage of the study, the inspection technology picks defects when they are relatively severe. The sensitivity of detecting defects can be improved by additional controlled field tests of timber utility poles and comparing the results with FE model to improve the analysis.
Chapter 7. CONCLUSIONS AND FUTURE DEVELOPMENT

The following findings from the research study are summarised based on the conclusions presented at the end of each chapter. The conclusions are grouped into five sections namely: (a) research background; (b) stress wave propagation; (c) FE analysis and results; (d) field testing and health assessment of timber utility poles; and (e) parametric study of timber utility poles. These conclusions address the research objectives presented in Chapter 1.

7.1 Summary and Conclusions

7.1.1 Research Background

1. The major drawback with timber utility pole is their decaying nature with time. The available inspection techniques in Australia do not predict accurately or adequately the residual strength and structural stability of timber utility poles which often results in premature replacement. Wang et al. (2008) studied in detail the in-ground decay of timbers in Australia and developed a tool predicting the rate of decay of timber with respect to species, location, treatment type and durability Class. There are several studies carried out looking into termite attack on houses with respect to location, climate and treatment type. Virtually no studies were made on timber poles. The termite prediction models used to evaluate the attack on housing clusters are not suitable in relation to timber poles.

2. Drilling inspection is the common technique along with visual and sound testing in Australia. Usually the drill holes are about 14mm in diameter (Energy Australia, 2006). Paradoxically the drilling holes cause poles to lose some of their strength. Periodic drilling inspections will result in a number of drill holes which cumulatively can result in severe strength reduction of a timber pole.
Factors such as smell, colour, drilling resistance, resulting shavings and the bite of the drill are important considerations when performing a drilling test. Hence, this inspection technique provides subjective results depending on personal observations and experience of the inspectors.

3. Micro resistance drilling is comparatively a non-destructive drilling test. The drill hole is small and has a negligible effect on the strength of timber poles. Actually, this method is an advanced adaptation of mechanical drilling, eliminating limitation of inspectors’ observations of pole characteristics and has the ability to record relative drilling resistance electronically. However, these data are limited to the drilling location. This method needs calibration and special consideration of the drill bits. The repetitive drilling action affects the sharpness of the drill bit. In addition, the resistance indices have to be developed for each and every timber species. The major drawback of this inspection method is multiple and time-consuming drilling would be required to map the area and extent of the decay in the other plane of a timber pole section. However, micro-drilling technology is not practiced in Australia.

4. Experimental modal analysis has been attempted to evaluate the performance of poles. The diagnostic parameters of experimental model analysis are natural frequency, mode shape and modal damping which can be estimated from vibration monitoring. The presence of damage or deterioration will cause changes in these parameters. Experimental modal analysis is generally difficult to apply for testing timber utility poles. Without an ongoing signature (as new condition) it is difficult to determine damages to poles as poles have many natural and induced defects which makes it very difficult to produce an accurate prediction of the dynamic properties.

5. SWP is widely used in the piling industry for the non-destructive integrity evaluation of concrete piles. There has been research conducted using stress waves to evaluate structural stability of timber bridges. The presence of decay greatly affects stress wave transmission time in the wood and this feature is used to perform the evaluation.
7.1.2 Stress Wave Propagation

6. The application of stress wave technology was successfully used to determine the embedded depths of timber piles by Douglas and Holt (1994). Dai et al. (2011) also reported field investigations undertaken to determine the embedded depths of transmission poles using SWP.

7. The transverse SWP testing methodology is based on applying an impulse force which creates a stress wave which travels along the timber utility pole then measuring the reflected stress wave with a geophone. It is essential to have a typical impulse force of at least 2500N into a timber utility pole to get a meaningful SWP velocity trace which represents the signature of the timber utility pole. When the force is below 500N, the results are invalid as it is proved to be insufficient to get the SWP throughout the pole.

8. Generally, the transverse SWP velocity for timber utility poles falls roughly between 800m/s – 1300m/s. The most common lengths of Australian and New Zealand timber utility poles lie between 6.0m – 18.5m. Hence, the total time of velocity trace recorded for one cycle of SWP will be limited to a maximum 45ms. The sampling rate of the system recording the trace needs to be between 15-20 kHz to get a good resolution of the trace. The duration of the impulse force input can vary from 1ms to 3ms depending on hardness of the pole of the impulse location while the impulse force may go up to a maximum of 8500N.

9. A developed Beta Pole Tester comprised of an impulse hammer, a geophone, a digital signal processor and a toughbook computer. The system collects the traces from the inspection of timber utility poles over a whole day from single charge. These traces can be later downloaded to another computer for further analysis.

10. The transverse SWP velocity data recorded during the testing needs processing to assess the integrity of timber utility pole. There are different recognised methods to filter and eliminate unwanted noise from the transverse SWP field
It is found that the Fast Fourier Transform (FFT) and Short Kernel Methods (SKM) are effective in interrogating dispersive wave propagations.

11. A preliminary transverse SWP trace analysis software has been developed using MATLAB programming. This provides the options of applying the filters either FFT or SKM and low pass, high pass filters.

7.1.3 FE Analysis and Results

12. FE modelling of SWP in the longitudinal direction was verified for a concrete pile with and without defects. This was later modified and applied to timber poles by investigating wave propagation in the longitudinal direction. These results were found to be consistent with the expected lengths and location of defects. Following the successful evaluation of SWP in the longitudinal direction, the transverse SWP was applied on a standing service pole and benchmarked with the results from FE models. FE results were found to be satisfactory when compared with field results.

13. Transverse directional SWP was further investigated for a pole in a pole yard. The pole was tested in different conditions as intact and having different defects. Three-dimensional non-linear finite element models (FE models) were developed to replicate the field tests of timber utility poles and benchmarked against the test results which resulted in excellent correlation. The results obtained from the FE models were benchmarked against the test data namely, for an intact pole, a pole with an above ground defect only and a pole with both above and below ground defects.

14. It was found that an intact pole will mainly have Start, Tip and Total reflection points in the SWP velocity trace. A pole with an above ground defect will have an intermediate reflection between the Start and tip reflection in the SWP velocity trace. A pole with a below ground defect will have an intermediate reflection between the Tip and Total reflection in the SWP velocity trace. A pole with above ground and below ground defects will have reflections between Start, Tip and Total reflection.
15. When there are multiple defects in a pole, there will be multiple reflections in the SWP velocity trace. In such cases, the identification of the exact location of each defect becomes complex. For such conditions, the operator will recognise that there are defects and can determine whether they are above or below ground. However, the determination of exact location or severity of defects would be difficult by analysing the SWP time domain data.

16. A number of timber utility poles were tested for Powercor and then destructively tested after transverse SWP inspection and analysis. The results obtained for defect detection from the SWP analysis were closely correlated with defect identification in the destructive testing.

7.1.4 Field Testing and Health Assessment of Timber Utility Poles

17. The Beta Pole Tester was incorporated into the normal pole inspection system in Christchurch and collected data for around 600 poles. The results were critically analysed for their SWP velocity for different features of poles. It was found from the field data that there is no significant change in transverse SWP velocity for pole parameters such as height, diameter, age and species.

18. The typical transverse propagation velocity in timber poles was found to be 1200m/s ±115m/s. This is regardless of the height, diameter, species and age of a timber utility pole.

19. An impulse force that is considered to be adequate for the SWP testing of timber utility poles should be above 2500N and less than 2.0ms in duration. If the force duration is long and corresponds to a low force magnitude, this indicates local damage at the location of hummer strike.

20. Based on analysis of the collected pole data in Christchurch, screening parameters for velocity, impulse magnitude and impulse duration have been
developed. These are presented graphically in Chapter 5 that can be used to screen a pole immediately when it is inspected.

7.1.5 Parametric Study of Timber Utility Poles Using FE Models

21. The effects on the transverse SWP velocity from different features of a timber utility pole namely, its height, diameter, tapering nature of the pole, different impulse forces and force locations and the severity of defect were investigated. The results corroborated the outcomes from the field testing results outlined above.

22. Changing the location of the impulse force from the ground line to above ground level will be beneficial in differentiating the reflections from the below ground defects to the tip and total reflection. However, defects within 0.5m above or below the impulse/geophone location are not possible to detect using this technology.

7.2 Recommendations for Future Research

This research project investigated the applicability of the transverse SWP technique to non-destructively examine timber utility pole. Although the technique detect significant defects and there locations, there remain some aspects where further research would be beneficial. A list of these is provided below.

1. Further study is needed to establish for a methodology for estimating severity of damage and correlating remaining life and residual strength of timber poles with defects. Signal processing and analysis programs need to be automated to identify and visualise the damage/defect and to estimate their severity.

2. Further investigations are required for simpler identification of multiple defect located above or below ground.
3. Investigation of the SWP results in the frequency domain and investigating the mobility and dynamic stiffness values for poles may prove to be beneficial to reveal more features about damages in poles.

4. Develop pole testing software where the inspector can simulate and analyse the field results in real time after the inspection to find the health state of the timber utility pole.

5. Perform further controlled tests and analysis to set acceptance limits for a Go/No Go system for line workers before they climb on poles. This would help preventing pole failure when worker are leaning against poles.
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APPENDICES

Appendix A. Pole Design Loads and Load Combinations

The loads and load combinations to be considered when designing a timber pole can be categorised as follows;

The self-weight of the pole & its component parts together with the weight of all attachments such as mountings & other brackets, luminaries, cables, transformers, signalling & communication equipment constitute the dead loads of a timber pole in its design.

Design snow and ice loads are generally based on the standards AS 1170.3 or NZS 4203.1, as appropriate. Further, detailed calculation of snow loads can be derived from the “Structural Design Requirements for Utility Poles” (Australian Standard AS-5604, 2005).

Wind loads acting on a pole, its component parts and any attachments including aerial conductors fixed to it, are determined either in accordance with the appropriate wind loading Standard (AS 1170.2 or NZS 4203) as appropriate or with the Standard AS 4676:2000 clause 3.4.

Where applicable, live loads and maintenance loads are considered to act concurrently on a pole and its component parts but only for the strength-limit state. It is not necessary for these loads to be taken to act concurrently with wind loads. The live loads for one person generally is taken as a concentrated vertical force of 1.4 kN, placed to cause the most adverse effect on the pole and its component parts. Each maintenance load is placed as a concentrated vertical force equal to the weight of the heaviest item of supported equipment placed at the relevant point of attachment to the pole.
Loads on poles and components parts arising from aerial cables in the consecutive spans supported by pole are determined in accordance with Clause 3.7.2 to 3.7.4 of AS/NZS 4676:2000. Further, there are several loads considered. They are mainly dead load of the cables, wind load on cable, aerial cable tension loads, stay loads, torsional loads etc.

Where a pole has a provision for the attachment of flags or banners, allowance are required to be made also for the additional force due to wind action on a specified maximum size of flag or banner. The guidance on the determination for forces arising from wind actions on flags or banners is given in Appendix G of AS/NZS 4676:2000.

There are several key features to be considered when designing the footings and in the foundation design of a timber pole. They are embedment depth, the footing itself, and the foundation. Further, extreme care should be taken with the soil type and properties before a pole is erected, for durability and strength concerns. Special attention should be paid to the ground water table and backfilling materials. Section 6 of AS/NZS 4676:2000 “Structural Design Requirements for utility Service Poles” reveals descriptively about the above topics.

The design load on a pole for a particular limit state is taken as the combinations of factored loads producing the most adverse effect on the pole at the location where such combinations are determined from. For regions not subjected to snow or ice, S (snow loading) is to be taken as zero and $F_{aT}$ only applies to poles supporting aerial cables.

**Combination for the strength limit state**

As a minimum, the following combinations are considered for the strength limit state;

(a) $1.1G + 1.5Q + 1.2S + 1.2F_{aT}$  
(b) $1.1G + M_i W_u + S + F_{aT}$  
(c) $1.1G + F_{eq} + F_{aT}$  
(d) $0.9 G + M_i W_u + F_{aT}$
Combination for the serviceability limit state

The following combinations are considered for the serviceability limit state;

(a) $G + Q + S + F_{aT}$ \hspace{1cm} A5

(b) $G + Q + W_s + F_{aT}$ \hspace{1cm} A6

(c) $G + W_s + 0.85(S + F_{aT})$ \hspace{1cm} A7

Where;  
$G$ - Dead loads  
$Q$ - Live loads and maintenance loads  
$S$ - Snow and Ice loads  
$F_{aT}$ - The actions or effects caused by cable temperatures  
$M_i$ - Structural importance multiplier  
$W_u$ - Wind loads at the permissible stress limit state  
$W_s$ - Wind loads at the serviceability limit state  
$F_{eq}$ - Earthquake loads
Appendix B. Sample Design of a Timber Pole

This appendix provides an example for the design of a timber utility pole with the following specifications (Horigan et al., 2000);

Red ironbark pole – Hardwood, Durability Class 1
Circular cross section
Mean Diameter – 300mm
Height of the pole – 14m
Preservation – Desapped, untreated.
This pole is for a local power cable conductor in Melbourne area.
Conductor – AAAC (1120) wires (Stranding & Dia - 7/4.75)

Relevant Loads and Design Action

The following section is accordance with AS/NZS 4676: Structural design requirements for utility services poles (2000)

Dead Load
Includes the self-weight of the pole and the weight of all attachments such as mounting & other brackets, luminaries, cables, transformers, signalling and communication equipment.
Dead Weight of the pole = Length x Cross section x Density
= 14 x \( \pi \times 0.3^2 / 4 \times 1200 \times 9.8/1000 \) kN
= 11.6 kN

Cable loads \( F_{aG} = w_g \times 9.8 \times 10^{-3} \times L_{eg} \) (kN) Clause 3.7.2 AS/NZS 4676:2000

\( w_g = 0.043 \text{ kg/m/strand} \)
\( L_{eg} = 100 \text{ m} \)
Then \( F_{aG} = 0.043 \times 7 \times 9.8 \times 10^{-3} \times 100 \)
= 2.947 kN

Assume others dead loads = 1.5 kN

So the Total Dead loads = 11.638 + 2.947 + 1.5 kN
= 16.1 kN

Wind Load.
The horizontal load on a pole from supported areal cables (\( F_{aw} \)) arising from wind at right angles to the span of the cables, shall be calculated from the following equation

Wind load \( F_{aw} = p_d \cdot d_c \cdot k_e \cdot L_w \) (kN) Clause 3.7.3 AS/NZS 4676:2000

Where:
\( p_d \) – design wind pressure in kPa
\( = 0.9 \times 0.85 \times 1.0 \times 1.2 = 0.918 \text{kPa} \)
\( d_c \) – nominal external diameter of the cable
\( = 14.3 \text{ mm} \)
\( k_e \) – span factor, = 1.0 for SLS
\( = 1.0 \text{ For } L_w=100\text{m} \)
\( = 1.0 \text{ for Strength limit state} \)
\( = 1.0 \text{ For } L_w=100\text{m} \)
\( L_w \) – the wind span
\( = 100 \text{ m} \)

So,
\( F_{aw} = 0.918 \times 0.0143 \times 1.0 \times 100 \) (kN)
= 13 kN

Areal cable tension load.
This calculation is made using AS/NZS 4676:2000
Assume the cable sag – 0.3m
then, the Tension,
\[ T = F_{aR} \times \frac{L}{8D} \]
Here
\[ F_{aR} = \left[ (F_{aG} + F_{aS})^2 + F_{aw}^2 \right]^{1/2} \]
\[ = \left[ 2.947 + 1.313^2 \right]^{1/2} \]
\[ = 3.226 \]
\[ \text{Tension} \quad T = 3.226 \times 100/8 \times 0.3 \]
\[ = 12.10 \text{ kN} \]

Loads on Flags and Banners
Assume there is a banner with a total face area of 2.0m² and the height to the centre is 5m

\[ F_{wf} = (0.024 + 0.008C_{df} \times W_g/b) \times p_d \times K_zK_T A_f \]
\[ F_{wf} = \text{Total force on the banner, kN} \]
\( C_{df} = \text{Drag Factor, 0.8} \)
\( W_g = \text{Mass per unit area if the wet flag material, 45g/m}^2 \)
\( b = \text{Dimension of banner at right angle to wind direction, 1m} \)
\( A_f = \text{area of one face of the banner, 1m}^2 \)

\[ F_{wf} = (0.024 + 0.008 \times 0.8 \times 45/1) 0.918 \times 0.85 \times 1.0 \times 1.0 \]
\[ = 0.25 \text{ kN} \]

---

**Figure B.2: Force diagram of electricity pole**

187
For the Strength Limit state we can exclude the case of snow for Melbourne.

Then, the appropriate combination will be;

\[ 1.1G + F_{eq} + F_{aT} \] ………………according to AS/NZS 4676:2000 Clause 3.9.4 case (b)

**For Bending Strength;**

\[ \phi M \geq M^* \]

\[ M^* = (1.1 \times 12.10 \times 10 + 0.25 \times 5) \]
\[ = 134.35 \text{ kNm} \]

\[ \phi M = \phi k_1 k_{20} k_{21} k_{22} k_d [f'_b Z] \]

Here;

\[ \phi = 0.90 \]
\[ k_1 = 0.57 \]
\[ k_{20} = 1.0 \]
\[ k_{21} = 0.85 \]
\[ k_{22} = 1.0 \]
\[ k_d = 0.90 \]
\[ f'_b = 100 \text{ MPa} \]

\[ Z = \pi \frac{d_p^2}{32} = \pi \frac{0.3^2}{32} = 8.836 \times 10^{-3} \]

\[ \phi M = 0.90 \times 0.57 \times 0.85 \times 1.0 \times 0.90 \times (100 \times 10^3 \times 8.836 \times 10^{-3}) \]
\[ = 467 \text{ kNm} \geq M^* (134.35 \text{ kNm}) \]
For Shear Strength;

\[ \phi V \geq V^* \]

\[ \phi V = \phi k_1 k_{20} k_{21} k_{22} k_d \left[ f'_s A_s \right] \]

\[ = 0.90 \times 0.57 \times 1.0 \times 0.85 \times 1.0 \times 0.90 \times (7.2 \times 10^3 \times \pi \times 0.3^2/4) \]

\[ = 199.73 \text{ kN} \geq M^* (12.10 \text{ kN}) \]

For Compressive Strength;

\[ \phi N \geq N^* \]

\[ \phi N = \phi k_1 k_{12} k_{20} k_{21} k_{22} k_d \left[ f'_c A_c \right] \]

\[ = 0.90 \times 0.57 \times 0.039 \times 1.0 \times 0.9 \times 0.85 \times 1.0 \times 0.90 \times (75 \times 10^3 \times \pi \times 0.3^2/4) \]

\[ = 73.03 \text{ kN} \geq N^* (16.085 \text{ kN}) \]

Checking for combined bending and compression strength

\[ \left( \frac{M^*}{\phi M} \right) + \left( \frac{N^*}{\phi N} \right) \leq 1 \]

\[ (134.35/467) + (16.085/73.03) = 0.508 \leq 1 \]

So, the pole properties and design parameters are satisfactory.

Footings and foundations

Assume, the soil bearing capacity is 150 kPa.

According to AS/NZS 4676:2000 Appendix I, the minimum below ground length of the pole (D) is given by:

\[ D = 3.6 H_R + (12.96 H_R^2 + 16.2 \text{ CM})^{1/2} \]

\[ \frac{2C}{\text{2C}} \]
H_R = 12.35 kN @ the height of 9.90 m (i.e. the resultant force of cable tension and banner force)

f_b = 150 kPa
b = 300 mm

C = f_b b = 150 x 0.3

M = H_R x h_r = 12.35 x 9.90; where H_R-horizontal force, h_r-height of the force acting

D = 3.6 x 12.35 + ( 12.96 x 12.35^2 + 16.2 x 150 x 0.3 x 12.35 x 9.90 )^{1/2}
  2 x 150 x 0.3

= 3.85 m < 4.0m
Appendix C. Main pole categories depending on treatment

Poles are categorized as below according to their intended purpose of use and treatment.

C1. Poles intended for use without full-length preservative treatment

Poles of any of the durability Classes 1 & 2 species which comply with the requirement of AS 2209-1994 Section 2 are usually supplied as poles for use without full-length preservative treatment. The poles are de-sapped, dressed or natural round as required. The sapwood remaining on untreated poles will often deteriorate quickly, especially at and below the ground line. It is always assumed that untreated sapwood makes no contribution to strength. The consequences of its loss (from the quick deterioration of the untreated pole sapwood) on the integrity of fastenings and similar fittings (such as brackets, pins, mounts) and on the appearance of the pole are also to be considered by the designer or the purchaser.

Unseasoned Poles are the poles inspected within 14 days of cutting for grading. For Inspection occurring after this period, proportional allowances are made for splitting, checking and other normal changes occurring during the drying of timber. In any case, for splitting and checking the limitations are not allowed to exceed those made for the seasoned poles. Poles are expected to be generally of sound wood, free from active termite attack, rot pocket and centre rot, but such imperfections are usually permitted to an extent specified according to the AS 2209-1994 Clause 2.2.1. Termites of the genus glyptotermes (one kind of dampwood termite) are known to survive the manufacturing process and cannot be controlled be the methods used for subterranean termites. So, poles exhibiting any evidence of their presence should be subjected to effective fumigation before acceptance for use in this category (Australian Standard AS-2209, 1994). Also the imperfections in heartwood are carefully considered before supply as per in AS2209-1994 clause 2.2.1.

When a seasoned pole is recommended, in addition to the requirements of an unseasoned pole, seasoned poles are required to comply with the following: the end split at the top are not allowed to exceed a numerical rating of 2 in Figure 3 and limited in length to 300mm. Further at the butt, end splits are not allowed to exceed a numerical
A rating of 7 in Figure 3 and limited in length to 900mm. Finally, the barrel check rates are not to exceed a numerical rating of 6 in Figure 4.

**C2. Hardwood poles intended for use after full-length preservative treatment**

Poles of any of the hardwood species in addition to complying with the requirements for the size and form in Section 2.1 are also required to be supplied for use after full-length preservative treatment such as creosote, waterborne multisalt (CCA) given in Section 5 of AS2209-1994.

In addition to the requirement of the unseasoned poles in Section 2.1, poles are allowed to be saw-trimmed, adzed or planned to remove branch shrubs, butt flare or other projections adversely affecting their utility or appearance, provided that on completion of this work they still comply with the requirements being followed. However, such machining is not permitted in the critical zone or below ground any closer to the nominal ground line than 1.5m. The poles are to be essentially of sound wood free from bostrychid borer holes, active termite attack, and internal rot pockets and centre rot but the imperfections are permitted according to Clause 3.2.1 in AS 2209-1994. The application of an appropriate prophylactic treatment is necessary as soon as possible after felling. It will prevent deterioration due to fungal decay or insect attack occurring before preservative treatment can be carried out.

In addition to the requirements of an unseasoned pole, seasoned poles are also required to comply with the following specifications. End splits and barrel check specifications are the same as for Poles intended for use without full-length preservative treatment but the barrel checks in the critical zone are required not to exceed the numerical rating of 2. At the time of treatment, generally sapwood borer holes and tunnels are limited as to not affect the structural integrity of the pole.

**C3. Softwood poles intended for use after full-length preservative treatment**

Poles of any of the softwood species and complying with the requirement with the size and form in Section 2.1 are required to be supplied for use after full-length preservative
treatment such as creosote, waterborne multi-salt (CCA) given in Section 5 of AS2209-1994. Usually it is difficult to visually distinguish between sapwood and heartwood in softwoods, especially some Pinus species. Generally, it is not possible to treat some of the softwood species such as Douglas fir, bunya pine to the requirements of the full length preservative treatments.

In addition to the requirement of the unseasoned poles in Section 2.1 the poles are required to be essentially of sound wood free from live insect attack. The imperfections are permitted according to Clause 4.2.1 in AS 2209-1994. Seasoned poles are expected to meet the requirements of unseasoned poles, and in addition the same condition of end splits of hardwood poles intended for use after full-length preservative treatment but the barrel checks in the critical zone are required not to exceed the numerical rating of 3 and the outside critical zone not to exceed the numerical rating of 7.
The Neutral Axis of a Pole

The neutral axis of a pole is an imaginary line, drawn through the pole where the timber fibres are neither in tension (being stretched) nor compression (being squashed). In Figure D.1, the fibres close to the neutral axis are stretched or compressed much less than the fibres on the near-side or far-side to the load. It is important to bore the pole in a position where the fibres are least strained, i.e. within approximately 10-15 degrees of the neutral axis, as shown by X or Y.

![Figure D.1: The Neutral axis of a pole](Source: Pole inspection & treatment procedures (Energy Australia, 2006))

The neutral axis is always at right angles to the resultant load on the pole; or the neutral axis is at right angles to the direction in which a stay wire would need to be erected to stay the pole, or 90° to the fall line of the pole. These statements mean the same thing, since the required direction of a stay wire is directly opposite to the resultant load on the pole.

D1 - In-line Pole without Service Mains

Assuming the worst case of wind direction at right angles to the conductors the maximum resultant load is also at right angles to the conductors and the neutral axis is parallel to the conductors. These loads act on the bore pole at X or Y, as shown in Figure D.2.
**APPENDICES**

**THE NEUTRAL AXIS OF A POLE**

**Figure D.2: Neutral axis of an in-line pole**

*Source: Pole inspection & treatment procedures (Energy Australia, 2006)*

**D2 - In-line Pole with Service Mains**

The loading of this pole is a combination of wind forces on the pole and conductors, and tension in the service mains. Service mains may be altered many times during the life of the pole, so the actual neutral axis may vary. As a rule, always take the neutral axis as being parallel to the line conductors. Bore pole at X or Y, as shown in Figure D.3.

**Figure D.3: Neutral axis of a pole with services**

*Source: Pole inspection & treatment procedures (Energy Australia, 2006)*
D3 - Angle Pole

Loading of an angle pole is a combination of wind loading on the pole and conductors and tension in the conductors. The maximum resultant loading on the pole is in the direction of the bisector of the included angle between the conductors. The neutral axis is at right angles to the bisector. Bore pole at X or Y, as shown in Figure D.4.

Figure D.4: Neutral axis of an angle pole
Source: Pole inspection & treatment procedures (Energy Australia, 2006)

D4 - Termination Pole

Loading of a termination pole is due to wind loading and tension in the conductors. The maximum resultant load is directed away from the pole in the direction of the conductors. The neutral axis is at right angles to the conductors. Bore pole at X or Y, as shown in Figure D.5.

Figure D.5: Neutral axis of an angle pole
Source: Pole inspection & treatment procedures (Energy Australia, 2006)
Appendix E. Sample Calculation for Decay of Timber Pole

E1. Manual Calculation with Basic Empirical Equations

The same pole parameters adopted for the sample design are used for the decay depth calculation.

Red ironbark – Hardwood, Durability Class 1
Circular cross section
Mean Diameter – 300mm
Sapwood thickness – 10mm
Height of the pole – 14m
Preservation – Desapped, untreated.
This pole is for a local power cable conductor in Melbourne.
Without full-length treatment.

Calculation of the decay depth after 25 years for the installation of the above mentioned pole and the inwards decaying process is found as the outwards decay will occur after 25 years in this case.

\[ d_i = \begin{cases} ct^2 & \text{if } t \leq t_{d_i} \\ (t - t_{lag})r & \text{if } t > t_{d_i} \end{cases} \]  

E1.

\[ c = \frac{d_0}{t_{lag}^2} \]  

E2.

\[ t_{d_i} = t_{lag} + \frac{d_0}{r} \]  

E3.

Assume, \( d_0 = 5 \text{ mm} \) {based on recommendation of Wang et. al (2008)}

The decay lag, \( t_{lag} \) (years), is given by;

\[ t_{lag} = 5.5r^{-0.95} \]  

E4.

Decay rate, \( r \)
untreated, timber = \( k_{\text{wood}} \times k_{\text{climate}} \)  

\( k_{\text{wood}} \), sap = 2.72  
\( k_{\text{wood}} \), heart = 0.23  
\( k_{\text{climate}} \) = 1.5  

Where; \( k_{\text{wood}} \) – wood parameter, \( k_{\text{climate}} \) – climate parameter.

\( R_{\text{untreated, timber}} = k_{\text{wood}} \times k_{\text{climate}} \)

\( (R_{\text{untreated, timber}})_{\text{Sap}} = 2.72 \times 1.5 = 4.08 \)

\( (R_{\text{untreated, timber}})_{\text{Heart}} = 0.23 \times 1.5 = 0.345 \)

the decay lag, \( t_{\text{lag}} \) (years), is given by;

\[ t_{\text{lag}} = 5.5r^{0.95} \]  

E4.

\[ t_{\text{lag}} = 5.5 \times 4.08^{0.95} = 1.44 \text{ yrs} \]

\[ t_{\text{do}} = t_{\text{lag}} + d_o/r \]  

E3.

\[ t_{\text{do}} = 1.44 + 5/4.08 = 2.66 \text{ yrs} < t \text{ (25yrs)} \]

\[ d_{t} = \begin{cases} \frac{ct^2}{t_{\text{lag}}} & \text{if} \ : t \leq t_{\text{lag}} \\ \frac{(t - t_{\text{lag}})r}{t_{\text{lag}}} & \text{if} \ : t > t_{\text{lag}} \end{cases} \]

E1.

for sapwood

\( d_t = ct^2 \)

10 = 5/2.66^2 \times t^2

t = 3.76 \text{ Yrs}

For Heartwood

Years for decay = 25-1.44-3.76
SAMPLE CALCULATION FOR DECAY OF TIMBER

\[ d_t = \begin{cases} 
\frac{ct^2}{(t-t_{lag})r} & \text{if } t \leq t_{d_i} \\
(t-t_{lag})r & \text{if } t > t_{d_i}
\end{cases} \]

E1.

d_t = (t-t_{lag})r

= 19.8 \times 0.345

= 6.83 \text{ mm}

So total decay depth will be = decay_{sap} + decay_{heart} = 10 + 6.83 \text{ mm in 25 years}

Calculated total decay depth in 25 years = 16.83 \text{ mm}
E2. Timber Service Life Tool Generated Results for Decay

Consider the same pole taken for the design which has a pole disc as below in Figure E.1.

![Figure E.1: Pole Disc of the pole designed](image)

From the above pole disc, it is possible to extract the specific details listed below;

- Height of the pole: 14 m.
- Timber species: Ironbark, red.
- Maximum load: 12kN.
- Preservative Type: Not preservative treated
- Pole treated on: Nov 1993.

The preservation type is expressed as a number and each and every number represents a specific treatment system. With manual inspection we can find the diameter of the pole. Further, it was located in Melbourne which is in hazard zone B. With this available data we can get an expected life prediction of the pole with the decay rate. Then, these available data is analysed with the software called “Timber Life” within the category of decay in-ground. Figure E.2 gives the input data on the tool for the analysis of the particular above case. The thickness of the sapwood is assumed to be 10mm. In any case, it is noted that section five of the Australian Standard AS 2209-1994 prescribes that if any of the durability Class 1 and 2 species described the Appendix C are intended for use after full-length preservative treatment then preservative penetration shall be to the full depth of any sapwood present, with an additional requirement that the depth of the sapwood must be no less than 12 mm. In the case that a pole is confirmed to be a
durability Class 1 species by a recognised authority, the minimum sapwood depth requirement does not apply.

The outputs of the same pole parameter from the tool developed by timber service life are shown in Figure E.3 and E.4.

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<th>Description</th>
<th>Decay in Ground Contact</th>
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<td>Hazard Zone</td>
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<td>Geometry</td>
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<td>300</td>
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<tr>
<td>Circular Sapwood Thickness</td>
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</tr>
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</tr>
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<td>Retention</td>
<td></td>
</tr>
<tr>
<td>Notes</td>
<td></td>
</tr>
</tbody>
</table>

Figure E.2: Timber Life input data.

Figure E.3: Timber life Result-01
Figure E.4: Timber life Result-02
Appendix F.  Strength Reduction with Drilling Inspection

Here the strength reduction with the drilling inspection is considered only with the second moment of area (I) at the particular cross section. The strength reduction is directly proportional to the change in second moment of area (I). It is considered that the drilling holes are made perpendicular to the surface of the pole.

Figure F.1 shows the sequence of drilling with the main line direction or with the neutral axis of the pole. Usually the drill holes are of 14mm diameter in a drilling inspection and a computation which follows in Table F.1 is based on inspection carried out with a 300mm diameter pole. Table F.1 shows the percentage reduction of the strength.

![Main line direction diagram](image)

*Figure F.1: Different drilling location and angle*

<table>
<thead>
<tr>
<th>Test Drills</th>
<th>2nd moment of area (Min) (x10^-6 m^4)</th>
<th>Reduction Percentage %</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>398.0</td>
<td>-</td>
</tr>
<tr>
<td>1</td>
<td>397.6</td>
<td>0.1</td>
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<tr>
<td>2</td>
<td>397.3</td>
<td>0.2</td>
</tr>
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<td>3</td>
<td>381.5</td>
<td>4.1</td>
</tr>
</tbody>
</table>
Appedniece G. Pole Testing Software Development

The following section summarises MATLAB main coding

```matlab
function varargout = SignalCalc_OutputFcn(hObject, eventdata, handles)

    PList = ['PCPoleInfo.xlsx'];

    [ndata, PList2, alldata] = xlsread(PList);
    PRun   = PList2(:,1);
    set(handles.File,'string',PList2(:,2));

    % Get default command line output from handles structure
    varargout(Douglas and Holt) = handles.output;

function Ana_Callback(hObject, eventdata, handles)

    set(handles.Ana,'string','UPDATE');

    %Data collection from Interface
    %
    %Scale settings
    XMn       = str2num(get(handles.TXmn,'String'));
    XMx       = str2num(get(handles.TXmx,'String'));
    FrX       = 1000;                                         %
    str2num(get(handles.FXmx,'String'));
    SKMAmpFr  = 25;                                           % Reducing
    str2num(get(handles.FXmx,'String'));
    SKMAmpVe  = 15;                                           % Reducing
    str2num(get(handles.FXmx,'String'));

    %Kernel Settings
    KFreq     = str2double(get(handles.SKMHz,'String'));
    % str2num(get(handles.SKMhz,'String'));
    Div       = 25/KFreq*500;
    Cyc       = str2double(get(handles.SKMcy,'String'));
    % str2num(get(handles.SKMcy,'String'));
    AveM      = str2double(get(handles.AMob,'String'));

    %Apply Filters
    Filter    = get(handles.Filt,'value');
    HPF       = str2num(get(handles.TYm,'String'));           % Anything
    LPF       = 1000;                                         % Anything
    anything

    % File Lab
    PoleID     = get(handles.File,'String');
    PoleIDE    = PoleID(get(handles.File,'value')); % Pole 1
```
Idex      = strcmp(PoleID, PoleIDE);
Index     = find (Idex);
PList     = 'PCPoleInfo.xlsx';

[RD, PList2, alldata] = xlsread(PList);
PRun      = PList2(:,2);
FileName  = PRun(Index(1));

PDir       = PList2(:,3);
PDr        = PDir(Index(1));

PSd        = PList2(:,4);
PSide      = PSd(Index(1));

PBT        = PList2(:,5);
PBoT       = PBT(Index(1));

PHA        = RD(:,6);
PHm        = PHa(Index(1));

PGP        = RD(:,7);
PGeo       = PGP(Index(1));

PDaA       = PList2(:,8);
PDAb       = PDaA(Index(1));

PDaB        = PList2(:,9);
PDe       = PDaB(Index(1));

FileName1 = strcat(num2str(Index), '.xlsx');

%%
%FFT settings

FDiv      = 5;                             % Diving frequency for resolution
StHz1     = 1;                             % Stiffness for plot 01
StHz2     = 1;                             % Stiffness for plot 01

%%
% Getting data from file

LabData1 = xlsread(FileNamex);
Timel   = LabData1(:,1);                  % sec (s)
Timel   = (Timel-Timel(1)); % Initialing the time after 0.75ms

TimeF   = LabData1(:,3);                 % sec (s)
TimeF   = TimeF - TimeF(1);
Velo1   = -LabData1(:,2)*2.0;            % Velo @ 0.3m (x0.25)
Forc    = LabData1(:,4);                 % Force at 0.3m

NotNum  = numnan(Timel);
m = size(Time1,1)-NotNum;       % number of data points in Time domain
m2 = size(TimeF,1);          % number of data points in Time domain FOR FORCE

%%
Pole&Hit settings

xxx = Time1(1);
yyy = Time1(m);
Tim = (yyy-xxx)/(m-1);     % Time step

xxx2 = TimeF(1);
yyy2 = TimeF(m2);
Tim2 = (yyy2-xxx2)/(m2-1);     % Time step FORCE

fs = 1/Tim;
dt = Tim;

fs2 = 1/Tim2;
dt2 = Tim2;

%%
Kernel data point numbers

SkmPL    = get(handles.SKM,'value');
AdSKM    = get(handles.AdSKM,'value');
VelFreq  = get(handles.VelFreq,'value');

%%
SKM Time shift modification

Del       = str2num(get(handles.Del,'String'));

for xx = 1:Del+m
    TimSKM(xx,1) = (xx-1)*Tim;
    VeloSKM(xx,1) = 0;
end

for xx = 1:m
    TimSKM(xx+Del) = Time1(xx)+Del*Tim;
    VeloSKM(xx+Del) = Velo1(xx);
end

TimSKM;
VeloSKM;

%%
Frequency$Fourier transform

Fine = FDiv*(fs/2^nextpow2(m));
n = Fine*2^nextpow2(m);       % Number of data points in frequency domain
Freq=(0:n-1)*fs/n;          % calculate FFT frequency

Fine2 = FDiv*(fs2/2^nextpow2(m2));
n2 = Fine2*2^nextpow2(m2); \hspace{1cm} \% Number of data points in frequency domain FOR FORCE
Freq2=(0:n2-1)*fs2/n2; \hspace{1cm} \% calculate FFT frequency FOR FORCE

V1 = fft(Velo1(1:m),n);
V1(1)=0;
Vmag1=abs(V1)*2/n; \hspace{1cm} \% calculate FFT magnitude

F = fft(Forc,n2);
F(1)=0;
Fmag=abs(F)*2/n2; \hspace{1cm} \% calculate FFT magnitude

\% Applying filter to the velocity
MM = 0.030/dt;
m3 = 0.025/dt;

VYMax = max(Velo1(1:MM))*1.1;
VYMin = min(Velo1(1:MM))*1.1;

if SkmPL == 1 || AdSKM == 1
\% Finding Kernel Frequency
if KFreq == 0
kFreq = Freq(find(Vmag1 == max(Vmag1),1));
else
kFreq = KFreq;
end

kma = 1/(Tim * kFreq);
r = round(kma);
ktme = TimSKM(1:r);

Kernel = 1*sin(Cyc*2*pi*kFreq*ktme);
SKM1 = zeros((m-r),1);

for j = 1:(m-r)
    for i = 1:r
        SKMX = VeloSKM(j+i-1).* Kernel(i);
        SKM1(j) = SKM1(j) + SKMX;
    end
end

Vk1 = fft(SKM1,n);
Vk1(1)=0;
kVmag1=abs(Vk1)*2/n; \hspace{1cm} \% calculate FFT magnitude

Velo1 = VeloSKM(1:m);

end

\% Velocity plot with/without SKM
if Filter == 1
    for fc = 1:n-1
if Freq(fc)>=HPF
    FilV1(fc,1) = V1(fc);
else
    FilV1(fc,1) = 0;
end

FVelo = ifft(FilV1,n-1);
FRVel = real(FVelo);

Fig11 = figure;
set(Fig11,'units','normalized','outerposition',[0 0 1 1]);

subplot(2,6,[7,12]);
plot(FRVel);
title(['Pole Velocity @ 0.15m after ',num2str(HPF),'Hz HPS filter applied']);
grid on;
xlabel('Time(s)'); ylabel('Velocity(m/s)');
xlim([0,1100]);

subplot(2,6,[1,5]);
plot(Time1,Velo1,'b');
hold;
title('Pole Velocity @ 0.15m before filter');
grid on;
xlabel('Time(s)'); ylabel('Velocity(m/s)');
xlim([XMn, XMx]);
ylim ([VYMin, VYMax]);
end

%%
% Finding Peaks
PKli = get(handles.Peaks,'string');
Pks = get(handles.Pks,'value');
NumOfPeak = str2double(PKli(get(handles.Peaks,'value')));

if Pks == 1
    IntCount = 1;
    rd = 0.90;

    while IntCount < NumOfPeak
        p = 0;
        Ref = VYMin/1.1*rd;

        % Peak velocit matrix
for l = 1:m3
    if Velol(l) < Ref
        p = p + 1;
        PkV(p,1) = l;
        PkV(p,2) = Time1(l);
        PkV(p,3) = Velol(l);
    end
end
IntCount = 1;

% Finding the ends of peaks
for a = 1:p-1
    if PkV(a+1,1) - PkV(a,1) == 1
        if a+1 == p
            PkE(IntCount) = a+1
            if NumOfPeak > IntCount
                rd = rd - 0.01;
            end
        end
    else
        PkE(IntCount) = a;
        if a > 1
            if PkV(a,2) - PkV(a-1,2) < 0.003
                SkPnt =
        end
        end
        IntCount = IntCount + 1;
    end
end
end
end
NoOfPk = length(PkE);
for y = 1:NoOfPk
    if y == 1
        t = PkE(y);
        PVel(y) = min(PkV(1:t,3));
APPENDICES  POLE TESTING SOFTWARE DEVELOPMENT

PVelTP(y) = find(PkV(:,3) == PVel(y));
PVelT(y) = PkV(find(PkV(:,3) == PVel(y)),2);

else
    t = PkE(y-1);
t2 = PkE(y);
PVel(y) = min(PkV(t+1:t2,3));
PVelTP(y) = find(PkV(:,3) == PVel(y));
PVelT(y) = PkV(find(PkV(:,3) == PVel(y)),2);

end

end

PkV
PVelTP
PVelT

end

%%
%Velocity Plot

if SkmFL == 1

    Fig5 = figure;
    set(Fig5,'units','normalized','outerposition',[0 0 1 1]);

    VYMaxSKM = max(SKM1(1:MM))*1.1/5;
    VYMinSKM = min(SKM1(1:MM))*1.1/5;

    subplot(1,1,1);
    plot(Time1(1:m-r),SKM1/Div,'black');
    hold;
    if AdSKM == 1
        plot(Time1,Velo1,'r');
    end

    title([Pole Velocity (',num2str(KFreq),' Hz, ',num2str(Cyc),' SMK) - ',PoleIDE]);
    grid on;
    xlabel('Time(s)'); ylabel('SKM Velocity(m/s)');
    legend('SKM Plot','Original');
    xlim([XMn,XMx]);
    % ylim ([VYMin,VYMax]);

end

Fig2 = figure;
set(Fig2,'Name',PoleIDE,'NumberTitle','off','units','normalized','outerposition',[0 0 1 1]);

subplot(2,6,[2,4]);

210
if AdSKM == 0
    plot(Time1,Velo1,'b');
    hold;
    ylim ([VYMin,VYMax]);
end
if AdSKM == 1
    plot(Time1,Velo1,'r');
    hold;
    plot(Time1(1:m-r),SKM1/Div,'black');
    legend('Original','SKM Plot');
end

title('Pole Velocity');
grid on;
xlabel('Time(s)'); ylabel('Velocity(m/s)');
xlim([XMn,XMx]);

subplot(2,6,[5,6]);

plot(Time1,Forc,'b');
title('Force input');
grid on;
xlabel('Time(s)'); ylabel('Force(N)','FontSize',8);
xlim([0,0.003]);
ylim ([0,8000]);

%%% Mobility BEFORE SKM

%Calculating Mobility before SKM screening
Mobility1 = Vmag1(1:n)./Fmag(1:n);
Mobility1(1)=0;

%Calculating average mobility
Posi = find(Freq>AveM);
Ind = Posi(1)-1;
Avg1= mean(Mobility1(1:Ind));

abc = Mobility1(2);

%Calculating dynamic stiffness
Poi11 = StHz1*FDiv+1;
Poi12 = Poi11+FDiv;

Stiff1 = 2*pi*(Freq(Poi12)-Freq(Poi11))/(Mobility1(Poi12)-
Mobility1(Poi11))/1000000;

MYMax = max(Mobility1(1:1000*FDiv))*1.1;

subplot(2,6,[7,10]);

if VelFreq == 0
    plot(Freq,Mobility1);
end
title('Pole Mobility');

xlabel(['Ave Mob <=',num2str(AveM),'Hz = ',num2str(Avg1),... ' m/s/N, Stiffness = ',num2str(Stiff1)]);
ylabel('Mobility (m/s/N)');
xlim([0,FrX]);
ylim([0,MYMax]);
grid on;

elseif VelFreq==1
    plot(Freq,Vmag1);
title('Pole Velocity in Freq');

    xlabel('Hz');
ylabel('Velocity m/s');
xlim([0,FrX]);

    ylim([0,MYMax]);
    grid on;
end

subplot(2,6,[11,12]);
plot(Freq(1:n),Fmag(1:n),'b');

xlim([0,1500]);
title('Applied Force');
xlabel('Freq(Hz)'); ylabel('Amplitude(N)','FontSize',8);
grid on;

%%
% Create textbox

PHmr = strcat(['Hammer @ ',num2str(PHm), 'm']);
PGeo = strcat(['Geophone @ ',num2str(PGeo), 'm']);
Side = char(strcat(PSide,' sides'));
FDirI =strcat(char(PDr),' dir.');
ButtipI= strcat([FDirI,' near ',char(PBoT)]);
PDAbI = strcat(['@ 1.6m ',char(PDAb),' mm']);
PDBeI = strcat(['@ 8.5m ',char(PDBe),' mm']);
Test = strcat('Test : ',PoleIDE);

% Pole Data
annotation(Fig2,'textbox',... [0.131467571644042 0.581168831168831 0.086481146304676 0.342532467532467],... 'String',{'TEST DATA','','10.6m, MM Pole','310mm, 190mm Dia','Test Number:',FileName,'Pole Length: 12.5m','Ham & Geo in:',Side,'Force applied in',ButtipI,'Damage:',PDAbI,'HorizontalAlignment','center','FontSize',8,... 'FitBoxToText','off','LineStyle','none');
% Pole Diameter: 370mm, 270mm', '', 'Hammer
at: ', PHmr, '', 'Geophone at: ', PGeop, ...
% HorizontalAlignment', 'center', ...
% 'FontSize', 8, ...
% 'FitBoxToText', 'off', ...
% 'LineStyle', 'none');

% PoleIDE.copy(DATA)
% clipboard('copy', data)

% if Filter == 1
% annotation(Fig11, 'textbox', ...
% [0.818766607013816 0.581168831168831 0.086481146304676
0.342532467532467], ...
% 'String', {'POLE DATA', '', 'Pole ID', PoleIDE, '', 'Pole
Length', Pht, '', ...
% 'Pole Diameter: ', Pdia, '', 'Pole Type: ', Pspc, '', 'Installed
Yr: ', PYr, '', ...
% 'Current Score', Psc, FN, '',
% HorizontalAlignment', 'center', ...
% 'FontSize', 8, ...
% 'FitBoxToText', 'off', ...
% 'LineStyle', 'none');
% end

% Peak data
% Create textbox

% if NumOfPeak == 6;
% AA = PVelT(1)*1000;
% BB = PVelT(2)*1000;
% CC = PVelT(3)*1000;
% DD = PVelT(4)*1000;
% EE = PVelT(5)*1000;
% FF = PVelT(5)*1000;
% AA = strcat('1st Peak: ', num2str(AA), ' ms');
% BB = strcat('2nd Peak: ', num2str(BB), ' ms');
% CC = strcat('3rd Peak: ', num2str(CC), ' ms');
% DD = strcat('4th Peak: ', num2str(DD), ' ms');
% EE = strcat('5th Peak: ', num2str(EE), ' ms');
% FF = strcat('5th Peak: ', num2str(FF), ' ms');
% DISP = char(AA,BB,CC,DD,EE,FF);
% elseif NumOfPeak == 5;
% AA = PVelT(1)*1000;
% BB = PVelT(2)*1000;
% CC = PVelT(3)*1000;
% DD = PVelT(4)*1000;
% EE = PVelT(5)*1000;
% AA = strcat('1st Peak: ', num2str(AA), ' ms');
% BB = strcat('2nd Peak: ', num2str(BB), ' ms');
% CC = strcat('3rd Peak: ', num2str(CC), ' ms');
% DD = strcat('4th Peak: ', num2str(DD), ' ms');
% EE = strcat('5th Peak: ', num2str(EE), ' ms');
% DISP = char(AA,BB,CC,DD,EE);
% elseif NumOfPeak == 4;
% AA = PVelT(1)*1000;
%     BB = PVelT(2)*1000;
%     CC = PVelT(3)*1000;
%     DD = PVelT(4)*1000;
%     AA = strcat('1st Peak: ',num2str(AA), ' ms');
%     BB = strcat('2nd Peak: ',num2str(BB), ' ms');
%     CC = strcat('3rd Peak: ',num2str(CC), ' ms');
%     DD = strcat('4th Peak: ',num2str(DD), ' ms');
%     DISP = char(AA,BB,CC,DD);
% elseif NumOfPeak == 3;
%     AA = PVelT(1)*1000;
%     BB = PVelT(2)*1000;
%     CC = PVelT(3)*1000;
%     AA = strcat('1st Peak: ',num2str(AA), ' ms');
%     BB = strcat('2nd Peak: ',num2str(BB), ' ms');
%     CC = strcat('3rd Peak: ',num2str(CC), ' ms');
%     DISP = char(AA,BB,CC);
% elseif NumOfPeak == 2;
%     AA = PVelT(1)*1000;
%     BB = PVelT(2)*1000;
%     AA = strcat('1st Peak: ',num2str(AA), ' ms');
%     BB = strcat('2nd Peak: ',num2str(BB), ' ms');
%     DISP = char(AA,BB);
% end

% annotation(Fig2,'textbox',
%     [0.137459807073954 0.524685147543997 0.163987138263665
%      0.0699083245036143],
%      function Rst_Callback(hObject, eventdata, handles)

close figure 1;
close figure 2;
close figure 3;
close figure 4;
close figure 5;
close figure 6;
close figure 7;
close figure 8;
close figure 9;
close figure 10;
close figure 11;

% --- Executes on button press in Ext.
function Ext_Callback(hObject, eventdata, handles)
close all;
clc
clear
### Appednice H. Christchurch Pole Data

<table>
<thead>
<tr>
<th>Field Run no</th>
<th>Pole ID</th>
<th>Pole Species</th>
<th>Velocity (m/s)</th>
<th>Year</th>
<th>Pole Height (m)</th>
<th>Pole Diameter (mm)</th>
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Appendix I. Powercor Pole Data

06/06/2012 09:58:35 - Run00001 (737) @ Ground

Run: Run00001
Pole ID: 737
Length: 16.8 m
Diameter: .... mm
Type: GG
Installed: 1971
Score: ...
MaxForce: 4322.3 N
Duration: 1.903 ms

FIELD COMMENTS:
None.

SIMULATION COMMENTS:
Average force over an average period. Multiple response from above ground section.
06/06/2012 09:59:56 - Run00003 (737) @ 1m

Run : Run00003
Pole ID : 737
Length : 16.8 m
Diameter : ... mm
Type : GG
Installed : 1971
Score : ...
MaxForce : 3182.97 N
Duration : 1.378 ms

FIELD COMMENTS:
None.

SIMULATION COMMENTS:
Low force over a longer period. Soft spot at testing point and multiple response.
06/06/2012 10:57:19 - Run00009 (703) @ Ground

FIELD COMMENTS:
None.

SIMULATION COMMENTS:
Good force over a shorter period. Multiple response from above ground section. Below ground section looks alright.
06/06/2012 10:58:16 - Run00011 (703) @ 1m

Run : Run00011
Pole ID : 703
Length : 16.8 m
Diameter : ... mm
Type : WS
Installed : 1972
Score : ...
MaxForce : 3021.46 N
Duration : 1.225 ms

FIELD COMMENTS:
None.

SIMULATION COMMENTS:
Low force over an average period. Soft spot around the point of inspection.
FIELD COMMENTS:
None.

SIMULATION COMMENTS:
Low force over a longer period. Strong indication of soft spots around the point of inspection.
06/06/2012 12:18:31 - Run00050 (738) @ 1m

- **Run ID**: Run00050
- **Pole ID**: 738
- **Length**: 15 m
- **Diameter**: ...
- **Type**: MT
- **Installed**: 1976
- **Score**: ...
- **MaxForce**: 4998.71 N
- **Duration**: 1.302 ms

**FIELD COMMENTS:**
None.

**SIMULATION COMMENTS:**
Average force over an average period. Possible below ground section change at 1.5m
06/06/2012 12:29:59 - Run00053 (751) @ Ground

Run : Run00053
Pole ID : 751
Length : 10 m
Diameter : ... mm
Type : ...
Installed : ...
Score : ...
MaxForce : 4063.83 N
Duration : 1.892 ms

Propagation: 1495 m/s
Underground: 2.09 m
Defect 3 Height: ...
Defect 3 Length: ...
Defect 2 Height: ...
Defect 2 Length: ...
Defect 1 Height: 4.2 m
Defect 1 Length: 0 m
Defect U Depth: ...
Defect U Length: ...

FIELD COMMENTS:
None.

SIMULATION COMMENTS:
Average force over a longer period. Possible above ground section change at 4.25m
06/06/2012 12:42:19 - Run00055 (755A) @ Ground

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<td>...</td>
</tr>
<tr>
<td>Defect U Length</td>
<td>...</td>
</tr>
</tbody>
</table>

**FIELD COMMENTS:**
None.

**SIMULATION COMMENTS:**
High force over a shorter period. Possible section change at 5.5m above ground. Looks like no problem below ground.
06/06/2012 12:42:58 - Run00057 (755A) @ 1m

Run : Run00057
Pole ID : 755A
Length : 10 m
Diameter : ... mm
Type : ...
Installed : ...
Score : ...
MaxForce : 4141.25 N
Duration : 1.333 ms

FIELD COMMENTS:
None.

SIMULATION COMMENTS:
Good force over an average period.
FIELD COMMENTS:
None.

SIMULATION COMMENTS:
High force over a longer period. Possible section change at 3.75m above ground. Looks alright below ground.
06/06/2012 13:52:28 - Run00077 (19) @ Ground

FIELD COMMENTS:
None.

SIMULATION COMMENTS:
Good force over an average period.
06/06/2012 14:47:51 - Run00100 (2) @ Ground

Run : Run00100
Pole ID : 2
Length : 15.2 m
Diameter : ... mm
Type : SB
Installed : 1950
Score : ...
MaxForce : 4795.61 N
Duration : 1.245 ms

Propagation: 1249 m/s
Underground: 2.83 m
Defect 3 Height: ...
Defect 3 Length: ...
Defect 2 Height: 7.02 m
Defect 2 Length: 0 m
Defect 1 Height: 5.47 m
Defect 1 Length: 0 m
Defect U Depth: ...
Defect U Length: ...

FIELD COMMENTS:
None.

SIMULATION COMMENTS:
Good force over a shorter period. Couple of responses from above ground at 5.5m & 7m.
06/06/2012 14:48:21 - Run00102 (2) @ 1m

Run ID: Run00102
Pole ID: 2
Length: 15.2 m
Type: SB
Installed: 1950
MaxForce: 2816.57 N
Duration: 1.513 ms

Propagation: 1310 m/s
Underground: 2.99 m
Defect 3 Height: ...
Defect 3 Length: ...
Defect 2 Height: 6.94 m
Defect 2 Length: 0 m
Defect 1 Height: 5.56 m
Defect 1 Length: 0 m
Defect U Depth: 2.16 m
Defect U Length: 0 m

FIELD COMMENTS:
None.

SIMULATION COMMENTS:
Low force over an average period. Couple of above ground section change and possible below ground section change. Soft spot around the inspection point at 1m high.
06/06/2012 15:50:05 - Run00013 (55-1204) @ 1m

Run : Run00013
Pole ID : 55-1204
Length : 9.15 m
Diameter : ... mm
Type : MM
Installed : 1961
Score : ...
MaxForce : 3313.86 N
Duration : 1.455 ms

Propagation: 1167 m/s
Underground: 1.75 m
Defect 3 Height: ... 
Defect 3 Length: ... 
Defect 2 Height: ... 
Defect 2 Length: ... 
Defect 1 Height: ... 
Defect 1 Length: ... 
Defect U Depth: ... 
Defect U Length: ...

FIELD COMMENTS:
None.

SIMULATION COMMENTS:
Low force over an average period. Indication of soft spots around the point of inspection.
06/06/2012 15:49:43 - Run00012 (55-1204) @ Ground

Run : Run00012
Pole ID : 55-1204
Length : 9.15 m
Diameter : ... mm
Type : MM
Installed : 1961
Score : ...
MaxForce : 5888.27 N
Duration : 1.025 ms

FIELD COMMENTS:
None.

SIMULATION COMMENTS:
High force over a shorter period. Looks alright
01/05/2012 12:41:49 - Run00161 (293) @ Ground

Run : Run00161
Pole ID : 293
Length : 14 m
Diameter : ...
Type : ...
Installed : ...
Score : ...
MaxForce : 9746.02 N
Duration : 1.027 ms

FIELD COMMENTS:
None.

SIMULATION COMMENTS:
Very damped signal. Insufficient energy transferred in to the pole with good impulse force recorded. Possible pole section reduction due to deterioration all along the pole.
FIELD COMMENTS:
None.

SIMULATION COMMENTS:
Very damped signal. Insufficient energy transferred in to the pole. Possible pole section reduction due to deterioration all along the pole.
01/05/2012 14:34:13 - Run00176 (48) @ 1m

Run : Run00176
Pole ID : 48
Length : 12.2 m
Diameter : ... mm
Type : MM
Installed : 1965
Score : ...
MaxForce : 7324.8 N
Duration : 1.068 ms

FIELD COMMENTS:
Double staked.

SIMULATION COMMENTS:
Good force over a shorter period. Possible section reduction 1.5m below ground and 5.75m above ground.
01/05/2012 15:07:49 - Run00185 (103) @ Ground

Run : Run00185
Pole ID : 103
Length : 10.5 m
Diameter : ... mm
Type : MM
Installed : 1965
Score : ... 
MaxForce : 9103.84 N
Duration : 0.677 ms

Propagation: 1013 m/s
Underground: 2.44 m
Defect 3 Height: ...
Defect 3 Length: ...
Defect 2 Height: ...
Defect 2 Length: ...
Defect 1 Height: 2.76 m
Defect 1 Length: 0 m
Defect U Depth: ...
Defect U Length: ...

FIELD COMMENTS:
None.

SIMULATION COMMENTS:
High force over a shorter period. Possible section change above ground.
FIELD COMMENTS:
None.

SIMULATION COMMENTS:
High force over an average period. Multiple response from above ground and possible section change above at (2.87-2.26m) 0.5m
01/05/2012 15:37:31 - Run00208 (392) @ Ground

Run                   : Run00208
Pole ID               : 392
Length                : 14 m
Diameter              : ... mm
Type                  : MS
Installed             : 1977
Score                 : ...
MaxForce              : 4566.62 N
Duration              : 0.591 ms

FIELD COMMENTS:
Transformer fixed at about the mid height from ground.

SIMULATION COMMENTS:
Damped return response. Average force over an average period.
01/05/2012 16:06:57 - Run00224 (18) @ Ground

Run: Run00224
Pole ID: 18
Length: 10.5 m
Diameter: ...
Type: MM
Installed: 1965
Score: ...
MaxForce: 5863.43 N
Duration: 1.479 ms

FIELD COMMENTS:
None.

SIMULATION COMMENTS:
Good force over an average period. Multiple response above and below ground. Possible section reduction on both section.
01/05/2012 16:09:38 - Run00234 (18) @ Ground

Run : Run00234
Pole ID : 18
Length : 10.5 m
Diameter : ... mm
Type : MM
Installed : 1965
Score : ...
MaxForce : 9143.03 N
Duration : 1.196 ms

FIELD COMMENTS:
Soft and delaminated.

SIMULATION COMMENTS:
Possible section change at 1.5m below ground and multiple above ground response.
08/05/2012 13:29:34 - Run00247 (76) @ Ground

Run : Run00247
Pole ID : 76
Length : 10.5 m
Diameter : ... mm
Type : MM
Installed : 1965
Score : ...
MaxForce : 6559.65 N
Duration : 1.232 ms

FIELD COMMENTS:
Water at about 0.5m. Water level was up to 2m.

SIMULATION COMMENTS:
High force over a shorter period. Multiple response from above ground and response from below ground.
FIELD COMMENTS:
Tested at 2m from ground. Water close to ground level.

SIMULATION COMMENTS:
High force over a shorter period, Looks alright.
08/05/2012 15:04:47 - Run00261 (20) @ Ground

Run : Run00261
Pole ID : 20
Length : 10.5 m
Diameter : ... mm
Type : MM
Installed : 1965
Score : ...
MaxForce : 3630.1 N
Duration : 2.122 s

Propagation: 1203 m/s
Underground: 2.91 m
Defect 3 Height: ...
Defect 3 Length: ...
Defect 2 Height: ...
Defect 2 Length: ...
Defect 1 Height: ...
Defect 1 Length: ...
Defect U Depth: ...
Defect U Length: ...

FIELD COMMENTS:
None.

SIMULATION COMMENTS:
Good force over an average period. Looks alright.
08/05/2012 15:28:11 - Run00279 (21) @ 1m

Run: Run00279
Pole ID: 21
Length: 10.5 m
Diameter: ...
Type: MM
Installed: 1965
Score: ...
MaxForce: 5566.22 N
Duration: 1.344 ms

Propagation: 1500 m/s
Underground: 6 m
Defect 3 Height: ...
Defect 3 Length: ...
Defect 2 Height: ...
Defect 2 Length: ...
Defect 1 Height: ...
Defect 1 Length: ...
Defect U Depth: ...
Defect U Length: ...

FIELD COMMENTS:
None.

SIMULATION COMMENTS:
Good force over a shorter period. Tested at about the mid height due to the water level.
08/05/2012 15:30:16 - Run00285 (21) @ 1m

Run: Run00285  
Pole ID: 21  
Length: 10.5 m  
Diameter: ... mm  
Type: MM  
Installed: 1965  
Score: ...  
MaxForce: 7869.61 N  
Duration: 1.002 ms

FIELD COMMENTS:
None.

SIMULATION COMMENTS:
High force over a shorter period. Looks Alright.