R&D of NDTs for Timber Utility Poles in Service – Challenges and Applications (Extension for Bridge Sub-Structures and Wharf Structures)

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Abstract. Round Timbers have been extensively used for utility poles especially electricity poles, wharf and timber bridge substructures in Australia, New Zealand and Canada. The industries in each country spends millions dollars annually on maintenance and asset management to avoid failure of the utility lines or wharf or bridge sub-structure, as such failure can be very costly and may cause serious consequences. Lack of information on their past/current conditions such as degree of deteriorations or/and damage below/above water level or ground level, greatly jeopardises asset management as replacement of such piles and poles creates a great financial burden on governments and asset owners.

Despite the development of various types of nondestructive testing (NDT) methods for evaluating the condition and the below ground quality of concrete piles, few methods have been developed for application on timber poles and wharf and timber bridge piles. Funded by Australian Research Council (ARC), an on-going R&D program was commenced recently at the University of Technology, Sydney in collaboration with the Electricity Network Association of Australia (AUSGRID) to develop a new reliable NDT to assess condition of the timber utility pole in-service including embedment length and above/below ground deterioration of poles. The project is composed of theoretical and experimental research covering timber material modelling, stress wave propagation and wave dispersion, soil structure interaction, probabilistic Finite Element modelling as well as active sensing technology, sensor network, advanced signal processing and data fusion. The project also targets on technology development, such as new NDT products for trial testing and implementation. Results of research and the developed technology can be extended to other applications such as for condition assessment of timber wharf and bridge substructure.

1. Background of the problem formation

Timber utility poles form a key infrastructure for electricity distribution systems and communication networks in Australia as well as in many other counties. Although underground lines or manufactured poles constructed from alternative materials may be practical in some locations, the cost to completely replace timber poles is likely to be prohibitive. When life cycle costs are considered, timber poles are considerably less expensive than manufactured alternative poles constructed of steel, concrete or fibre-reinforced plastic (FRP) composites and the only material type which is renewable.
Moreover, non-timber poles have different conductive and/or dynamic strength properties and often require different fittings.

There are over 5 million in-service timber utility poles currently throughout Australia’s energy networks, which is more than 80% of total utility poles in the energy network. Anecdotal evidence suggests that up to 70% of the timber poles currently in-service were installed over the 20 years, and these poles are likely to require replacement or remedial maintenance over the next decade [1]. Based on the assumption that a new preservative-treated timber pole costs five hundred dollars, 1.75 billion dollars would need to be invested to fund the acquisition of 3.5 million replacement timber poles that may soon be required.

Lack of reliable information concerning their in-service condition, including the degree of deterioration or damage below ground level makes it extremely difficult for the asset managers to make decisions on the replacement/maintenance process with due consideration to economy, operational efficiency, risk/liability and public safety. The decision to replace in-service utility poles is currently based on traditional methods for determining a timber pile/pole conditions by visual inspection and sounding techniques. Unfortunately, these methods may prove inconclusive and in many cases are based on interpretation of information and not measurable parameters which may lead to unnecessary replacement of the piles/poles. As an example, each year about 30,000 electricity poles are replaced in the eastern states of Australia, despite the fact that up to 80% of these poles are still in very good and serviceable condition.

This on-going research aims at development of a cost-effective Non-Destructive Testing (NDT) technique for determination of condition and remaining strength, including the below ground butt region, of timber utility poles in service. The proposed project will utilise the latest developments in damage detection, advanced signal processing and numerical modelling techniques to fill gaps in NDT applications of in-service timber structures.

2. Brief Review of Current Stress-Wave-Based Methods for Pile/Pole Structures

NDTs utilising stress wave for the determination of the unknown depth of foundations and defects of piles/poles can be divided into two groups: Surface NDT, if access is required only at the surface of the testing structures, or Borehole NDT, if a borehole is drilled close to the foundation structure and extends along its length [2-8]. Considering the cost/benefit, complexity and applicability in the field, the NDT to be considered in this research will be limited to the surface methods. Therefore the current available NDTs relevant to this research are Sonic Echo/Impulse Response, Bending Waves and Ultraseismic methods.
**Sonic Echo(SE)/Impulse Response (IR)**

Sonic Echo/Impulse Response (SE/IR) tests\[8-11\] can be used to detect defects, soil inclusions and pile necking, diameter increases as well as approximate pile lengths. SE/IR tests are performed on drilled shafts and driven piles (concrete or timber) or auger-cast piles.

The method requires a measurement of the travel time of stress waves (time domain), and the Impulse Response method uses spectral analysis (frequency domain) for interpretation. In both (SE/IR) tests, the reflection of longitudinal compressive waves from the bottom of the tested structural element or from a discontinuity such as a crack or a soil intrusion is measured. The generated wave from an impulse hammer travels down a shaft or a pile until a change in acoustic impedance is encountered where the wave reflects back and is recorded by a receiver placed next to the impact point. The main problem is that the method lacks reliability and robustness. Since the results analysis greatly rely on signal processing and the interpretation of data in graphic form, it introduces large uncertainty that can lead to unreliable results often evident in practice. This problem can be overwhelming when the defect/damage is coupled with unknown depth and geotechnical condition.

**Bending Dispersive Waves**

This method uses flexural (bending) waves \[9-11\] that are highly dispersive in nature to determine integrity and unknown depth of deep foundations. The key feature of this method is that only a horizontal blow is required, which is easy to apply to the side of a substructure. Since the method involves striking the pile on a side and placing the receivers on the side of the pile, the method is potentially useful in cases where the top of the pile is obscured by a structure. There is complicated signal processing requiring expertise in this method which may be a source of error in practice. The complication of signal processing can become particularly problematic when the impact cannot be exerted from the end of the pole/pile. When impact is exerted between the ends the reflect waves interfere each other cause the distortion in measured signals. In addition, it also needs the consideration of the defect/damage being coupled with unknown depth and geotechnical condition.

**Ultraseismic (US)**

The Ultraseismic (US) method \[9-12\] is performed to evaluate the integrity and determine the length of shallow and deep foundations. The method is particularly useful in testing abutments and wall piers of bridges because of the relatively large exposed areas available for testing. Ultraseismic method was developed in response to the difficulty encountered in interpreting the Sonic Echo/Impulse Response and Bending wave methods from complex structures (such as a bridge) where many reflecting boundaries are present. The method
uses multi-channel, three-component recording acoustic data followed by computer processing techniques adapted from seismic exploration methods. This method can be used to obtain two-dimensional reflection images from complex structures, such as bridges, buildings, and dams. Multiple-channel recording allows for differentiation of bottom echoes from other complex wave modes far more reliably than single-channel Sonic/Pulse Echo or Bending wave methods. For very deep foundations, echoes from the bottom may not be obtained because of the attenuation of energy in the surrounding soil. Costly and requiring extensive instrumentation and complex signal processing analysis are the main drawbacks.

3. Research Challenges and Proposed Methodology

3.1. Research gaps and challenges

The literature study suggests that there are very limited research has been conducted in surface wave based NDT on pole applications while applications on piles are rather field-practice-driven from practicing engineers and consultants which are based on the methods developed few decades ago. In terms of development of new wave based NDTs for pole structures, the some research gaps and challenges in are suggested by the authors:

1. **Lack of understanding the complication on generated waves/wave modes and needs for developing signal processing approach to deal with the problem**

   Due to practicality, generating stress waves from top of poles is not feasible. A practical solution is to induce stress waves by impacting a pole aside at a reachable height above ground level by an angled wave guided (Figure 2). However, this approach will result in not only three simultaneous wave types (longitudinal, flexural and surface waves) but also both up-travel and down travel waves for each type of the waves. Moreover, since NDTs for assessments of embedded pole/pile rely on the reflected wave for analysis, it impose a great challenge on the data processing and analysis. Understanding the behaviour of the generated stress waves in poles due to the side impact holds a key for the solution of the problem.

2. **Lack of understanding the complication on timber material including its damage/defect and needs for developing appropriate models to adequately reflect such complexity.**

   Being a naturally grown material, timber exhibits complex material property with great variations and uncertainties. The problem is further complicated when natural defects, deteriorations and fungi/terminate damage are involved. Accurate and computational efficient numerical or/and semi analytical models for the utility poles are critical. Proper damage models should also be developed and verified by experimental investigations. Damage “figure prints” and damage index need to be established and numerical model updating techniques are also required.

3. **Lack of understanding the impact of the environment including soil embedment and needs for incorporating such factors in modelling and signal processing.**

   Complication of the environmental factors, including embedment soil and moisture in poles and soil, presents a significant challenge on development NDTs for accurate and reliable condition assessment of poles. Understanding impacts of these factors and incorporating them in the modelling and signal processing holds a key for development of a reliable and robust NDT for in-service pole assessment.
3.2. Strategy to the solution of the problem

The proposed research strategy is to incorporate latest development in the related research fields and to combine throughout theoretical and numerical research with extensive experimental investigations including laboratory testing, pole-yard testing and field testing for the solution of the problem. For this purpose, the research is divided into two main phases: namely the passive sensing phase and the active sensing phase.

Phase I: Passive sensing
This phase has two main purposes: i) to meet industry partner’s need for a simple and cost-effective screening tool for determination of soundness and embedment length of in-service poles and ii) to investigate some fundamental issues related to modelling, signal processing and pattern recognition. Research in this phase focuses on understanding of stress wave behaviour in timber poles under typical soil embedment condition with/without damage. Such understanding is critical as it not only forms a base for deriving pattern or “finger print” to identify unhealthy status poles but provides rationale and techniques to analyse and bound influences from uncertainties of materials and environment.

Phase II: Active sensing
This phase aims at developing a new generation of wave based NDT method, combining active sensing technology, sensor network, information fusion techniques incorporating hardware and software development. Active sensing system will be developed utilising piezoelectric (PZT) sensor/actuator with networking capacity. This phase will heavily depend on the research findings and development results from the phase I. Instead of passively recording data, the new technology will allow the device to intelligently interrogate the testing structure to obtain needed information such as healthy status and underground condition of poles.

4. Some Research Findings and Progress to Date

4.1. Experiments

As experiments play a key role in the project, extensive experimental testing program is set up for this research including laboratory testing, pole yard testing and field testing before and after decommissioning of utility poles (see Fig. 3).

Laboratory experiments (Figure 3(a)): laboratory experimental investigations allow investigations of wave behaviour under isolated conditions as well as examination of damage patterns inherent in stress wave signals under isolated influencing factors such as material imperfection, soil condition and various damage scenarios.

Pole yard experiments (Figure 3(b)): the industry partner organisation has a pole yard facility where selected utility poles can be installed and tested with various influencing factors including underground embedment lengths, damage/deteriorations.

Field experiments (Figure 3(c)): The field investigations and verifications will be conducted on “to-be-decommissioned” electricity power lines. After testing and evaluation using the developed NDT method, the poles will be pulled out and cut into sections to verify the detection results. Numerical model can also established base on post-mortem

Figure 2. Wave based NDT for a utility pole
autopsy of the tested poles. Some selected poles may also be statically tested to failure to provide strength capacity to verify the numerical evaluation.

4.2. Finite Element (FE) modelling of a timber pole and damage

Development of an accurate and computational efficient numerical model is another key for this research. The challenges faced in this research in terms of development numerical models includes timber material modelling, soil and pole interaction on wave propagation and damage/deterioration modelling etc.

At a low strain level (e.g. less than 0.03), timber exhibits linear elastic behaviour [13] and therefore can be modelled as linear elastic orthotropic material. Since the strain induced by the hammer impact is usually small (below 0.001), in this research timber poles will be modelled as an orthotropic linear elastic material. In addition, layered material modelling may be considered to take into account effects of annual growth rings of timbers. The transversely isotropic modelling will also be considered for computational efficiency. Similarly, soil can be simulated as linear elastic for low strain testing ($\varepsilon < 10^{-3}$) [14], which is the case in this research ($\varepsilon < 10^{-5}$).

Damage of wood can be caused by several factors including insects attack, fungi, weather, age and mechanical damage from vehicles. For embedded timber poles, wood decay typically occurs just below the ground line. Several types of wood decay can be identified and are depicted in Figure 4 [15] In this research, the above damage or combination of the damage will be simulated by either reducing the sectional elastic modulus or eliminating sectional elements in FE models.

Figure 3. a) Laboratory test set up; b) pole yard test set up and c) field testing

Figure 4. Possible decay patterns of in-ground sections of utility poles

Figure 5. Comparison of experimental results and numerical simulation using different interface models: a) Perfectly bounded (left) and b) frictional contact (right).
4.3. Discussion on results and findings

For soil-pile interaction, interfaces are commonly simulated in two ways: perfectly bonded interface (coupling method) or frictional interface (contact method). The frictional interface allows slipping and gapping between the soil and the pile, which represents the real behaviour more accurately. However, it takes more computational time and computer resource. Hence, if slipping and gapping is negligible or will not influence the analysis result, perfect bonding using the coupling method can be applied [16]. In this research, both methods are considered and the experimental verification shows that coupling method is more adequately capture the behaviour of the stress wave in the pole (Figure 5).

Figure 6 highlights importance of the numerical investigations in this research. Time histories of wave propagation in each node of the FE model is plotted out in a seismic graph. It can be seen clear that since the impact was impact at the side of pole near ground level, up-travel and down-travel wave are generated simultaneously. The travel-down wave at bottom of the pole will produce reflection and refraction at the interface. The refraction wave in the soil travels with very low velocity. There is a wave generated from bottom of the pole travel along in the pole with same velocity. At some part of the pole up- and down-travel waves interfere each other for which sensors should avoid such locations or corrections can be made by signal processing. The velocity of wave in the pole reduces when waves travel in the embedded part of pole.

![Figure 6. Seismic graph from FE results](image)

Figure 7. Dispersive curves of transversely isotropic timber pole with different Elastic Modulus: a) Longitudinal wave (left) and b) bending wave.

The uncertainty of elastic modulus has less impact on bending wave or longitudinal wave at low frequency (Figure 7). However, cut-off frequencies for various wave modes can be greatly affected by modulus which may resulted in presence of unwanted waves.
5. Conclusions and the Next Stage Research

This paper reports an on-going research and development project on NDTs for condition assessment of timber utility poles in service. It provides background and justification for the research and development and highlights challenges and issues facing such development. Due to the paper limit, most results and findings to date could not be provided. Some of them can be found in listed publications [17-18]. For the next stage research focuses will be on damage pattern extraction, numerical model updating, active sensing, sensor network, pattern recognition and information fusion.

Acknowledgement

The authors wish to acknowledge the funding and supports of Australian Research Council and Ausgrid on this project.

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