DETECTION OF TERMITE DAMAGE IN HOOP PINE (*ARAUCARIA CUNNINGHAMII*) TREES USING NONDESTRUCTIVE EVALUATION TECHNIQUES

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LIN CJ, HUANG YH, HUANG GS, WU ML & YANG TH. 2016. Detection of termite damage in hoop pine (*Araucaria cunninghamii*) trees using nondestructive evaluation techniques. The purpose of this study was to investigate the standard parameters of undamaged, living hoop pine trees using nondestructive evaluation techniques. This study also detected stress wave velocity tomogram and corresponding velocity maps of hoop pine trees with and without termite damage. The range of demarcation between termite-damaged and undamaged wood occurred at transversal stress wave velocities of 988–1164 m s^{-1}. Different nondestructive evaluation parameters could serve as indices for diagnosing standard values. Transversal velocity tomogram and corresponding velocity maps of hoop pine trees with and without termite damage could detect the general location and area of wood deterioration.

Keywords: Stress wave, tree risk assessment, visual tree assessment

INTRODUCTION

The hoop pine (*Araucaria cunninghamii*) tree is a common landscape tree in Taiwan. In recent years, studies of endangered trees have shown that hoop pine suffers from termite damage and fall without warning. This could lead to human casualties or result in property loss. Trees suffering from termite damage topple easily due to failure occurring at the base of the trunk. Termites are considered as important forest pests in Taiwan. *Odontotermes formosanus*, *Coptotermes formosanus* and *C. gestroi* build mud tubes on tree bark and/or also cause bite damage in the trunks of living trees (Lee et al. 2011).

Concerns about public safety and urban tree conservation have strongly led to development and application of rapid, precise and cost-efficient diagnostic techniques to detect decay and other types of structural defects in trees (Wang & Allison 2008). Standing trees must be evaluated in order to maintain in-situ structural safety for tree risk assessment. Various nondestructive evaluation techniques have been employed to detect decay and deterioration in trees in order to identify hazardous trees. Visual tree assessment includes visual inspection of the tree to look for external evidence of internal defects, instrumental measurements of internal defects and evaluation of the residual strength of the wood (Mattheck & Breloer 1994). Arboriculturists consider visual tree assessment essential for evaluating tree defects and providing basic information about tree growth performance and stability.

Stress and ultrasonic wave evaluation measurements of wood have proven to be effective parameters for detecting and estimating deterioration in tree stem and wood structures (Lin et al. 2000, Pellerin & Ross 2002). In recent years, nondestructive evaluation techniques have been developed for tomographic investigations. Acoustic tomographic measurements in wood have been found to be effective in detecting and estimating decay in tree stems (Wang et al. 2009, Lin et al. 2013). Acoustic tomography has been proven to be the most effective technique for detecting internal decay, locating the position

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of defects and estimating their size, shape as well as characteristics.

Nondestructive evaluation techniques can be used in combination to achieve better accuracy in determining the location and extent of wood deterioration. In this study, we used stress wave, drilling resistance, lateral impact vibration, fractometer and density profile techniques to detect evaluation parameters of living undamaged hoop pine (*Araucaria cunninghamii*) trees. We investigated stress wave velocity tomogram and resolved corresponding stress wave velocity (velocity) maps of hoop pine trees with and without termite damage to understand the degree and extent of trunk deterioration.

MATERIALS AND METHODS

The experiment was carried out in-situ on 12 undamaged hoop pine trees (group A) in Taipei, Taiwan. These trees were inspected in 2014 when the trees were about 35 years old with diameters at breast height (dbhs) of 25–40 cm. Multiple stress wave measurements were carried out at eight equidistant points (eight probes) on the trunks. All sensors were located in the trees at about 30 cm above ground. A transducer was connected at an angle of 90° to each trunk axis to detect propagated travel time and stress waves. The transmitter probe was first positioned at point 1 with stress wave pulses acquired by the receiver probe at the other seven points. Hammer tapping was done from points 1 to 2, 3, 4, 5, 6, 7 and 8. Measurements were repeated with the transmitter probe positioned at each point, thus giving 28 (for a complete round trip: 7 receiving probes × 8 transmitter probes ÷ 2 [the same path was measured twice]) independent propagation time measurements for each investigated section. A complete data matrix was obtained through this measurement process at each test location.

The circumference of each cross-section and distance between sensors were measured using tape measure. These measurements served as inputs for the system software to map approximate geometric form of the cross-section. Upon completing acoustic measurements, a tomogram was constructed for each cross-section using the ArborSonic software (version 5.1.48, 2011). Due to differences in species and paths, a two-dimensional (2D) image was obtained using the same software based on original stress wave transmission times (no adjusted and regularised times) to understand the experimental values in this study. To quantitatively assess the tomograms, all corresponding stress wave velocities at each pixel of the tomogram were further calculated by visualising and converting the tomograms into yield stress wave velocity maps of the cross-sections (Figures 1–3).

After the stress wave characteristic information of each cross-section was tabulated, the resonant frequencies were measured using a portable lateral impact vibration meter to diagnose the wood quality inside a standing tree. The product d × f of the resonance frequency f of the vibration or the sound of an impacted tree stem and the stem diameter d served as the diagnosis index.

Drilling resistance was conducted using a F500 resistograph. Drilling paths ran in radial direction from the bark to the pith of a trunk cross-section. Sound wood is dense, hard in texture and has high resistance to drill penetration. In contrast, severely decayed wood is less dense, softer in texture and has reduced drilling resistance (Pokorny 1992). Cores measuring 5 mm diameter were cut from the trunk using increment borer. A fractometer was used to evaluate the crushing strength of core samples (in green state) in the bark to the pith direction at an interval of 6 mm. Finally, a core specimen was mounted and processed into slices (wideness × thickness = 17 × 2.0 mm) for X-ray densitometric scanning. The conditioned slices (air-dried) were subjected to a direct-reading X-ray densitometer to determine tree ring (wood) density profile. Table 1 summarises these nondestructive evaluation methods involved in tree assessment in this experiment.

The experiment was also carried out in-situ on 46 hoop pine trees in Tainan (35 trees) and Taipei (11 trees), Taiwan. These trees were investigated in 2014 when the trees were about 30–40 years old with dbhs of 30–40 cm. Tree trunk deterioration was detected by stress wave tomography (using the same method described above). After the 2D image of each cross-section provided by the tomogram was tabulated, the sampling core method was conducted using an increment corer to determine the wood deterioration (with or without termite damage). In total, the termite damaged (group C) and

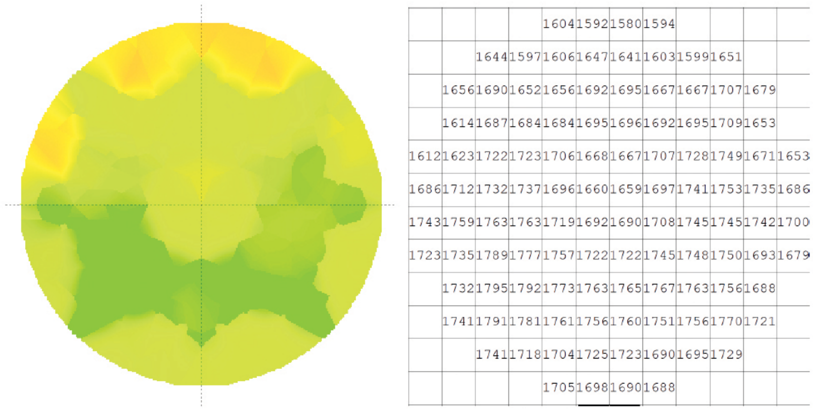

Figure 1 Stress wave velocity tomogram and the corresponding stress wave velocity map grids of an undamaged tree (group B, velocity range 1367–1806 m s^{-1})

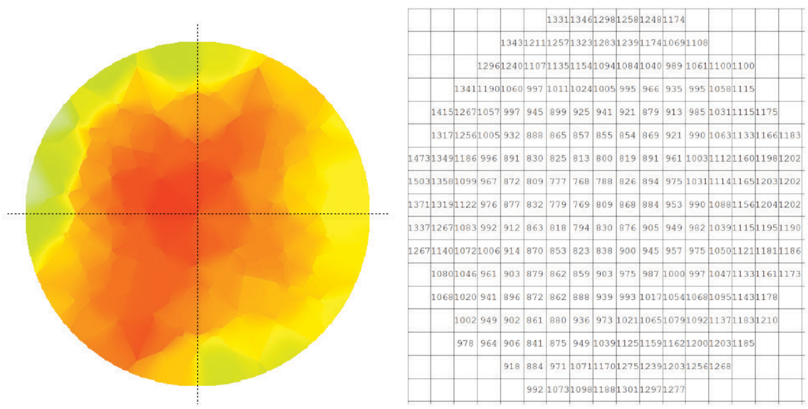

Figure 2 Stress wave velocity tomogram and the corresponding stress wave velocity map grids of a termite damaged tree (group C, velocity range 643–1797 m s^{-1})

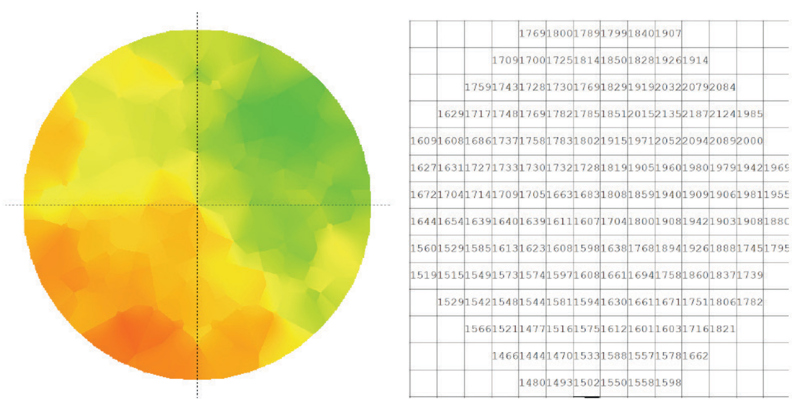

Figure 3 Stress wave velocity tomogram and the corresponding stress wave velocity map grids of a lean tree (group B, velocity range 1235–2202 m s^{-1})

Table 1 Assessment of standard values (reference) in undamaged trees by different nondestructive evaluation techniques

Method	Evaluated parameter
Acoustic device 2D tomogram	Transversal acoustic velocity (m s^{-1})
Lateral impact vibration	Diameter × frequency (m Hz)
Drilling resistance method	Drilling resistance value (%)
Increment borer	Observation of core by visual
Fractometer	Crushing strength (green, MPa)
X-ray wood density profile	Density (air dried, g cm^{-3})

undamaged trees (group B) amounted to 28 and 18 trees respectively.

RESULTS

The average minimum and maximum stress wave velocity values were 1154 and 1669 m s^{-1} for the 12 undamaged hoop pine trees (group A) respectively (Table 2). The mean velocity of tomogram was 1411 m s^{-1}. Average lateral impact vibration performance, drilling resistance value, green crushing strength and air-dry wood density were 327.6 m Hz, 39.7%, 26.2 MPa and 578 kg m^{-3} respectively (Table 3). Transversal stress wave velocity, lateral impact vibration performance, drilling resistance value, green crushing strength and air-dry wood density of the undamaged tree stem served as the indices of diagnosis or standard reference value.

Average minimum and maximum stress wave velocity values were 1164 and 1800 m s^{-1} for the 28 undamaged hoop pine trees (group B, undamaged trees) respectively (Table 4). The mean velocity of tomogram was 1482 m s^{-1}. Average minimum and maximum stress wave velocity values were 847 and 1642 m s^{-1} for the 18 undamaged hoop pine trees (group C) respectively (Table 5). Mean velocity of tomogram was 1258 m s^{-1}. Average velocity values (minimum, maximum and mean) of trunks in termite-damaged trees (group C) were clearly lower than those of undamaged trees (group B). Moreover, the average velocity values of group A were similar to those of group B (undamaged trees) (Tables 2 and 4). Minimum velocity values (1154–1164 m s^{-1}) could be considered as the threshold values of diagnosis by stress wave velocity tomogram.

The stress wave velocity tomogram and corresponding stress wave velocity value maps were examined for the 18 termite damage (group C) and 28 undamaged (group B) hoop pine trees (Figures 1–3). None of the tomograms of undamaged hoop pine trees displayed distinct pattern of high and low velocity in the cross-section of the stem (Figure 1). However, all tomograms of termite-damaged hoop pine trees displayed distinct patterns of high velocity (undamaged wood area) at the stem perimeter and low velocity in the stem centre (damaged wood area) (Figure 2). Moreover, the tomogram of abnormal hoop pine trees (lean) displayed distinct pattern of high velocity at the stem perimeter side (Figure 3). Maximum velocity value of lean hoop pine trees showed higher velocity value than those of normal, non-lean trees. Standard deviations of average maximum velocity values showed the following trend: groups C > B > A (Tables 2, 4 and 5). The numbers of lean hoop trees (different degrees) displayed the similar trend, i.e. groups C > B > A.

DISCUSSION

Observation in the field showed two situations where trees were damaged by termite. First, wood deterioration due to termite bites developed as internal xylem (from unnderground) penetrated outwards to the bark side and from the root or trunk collar upwards to the trunk (e.g. *Coptotermes formosanus*). Termite damage inside a tree was not always visible. Trees suffering from termite damage topple easily with failure occurring at the base of the trunk (Figure 4). In the second situation, trunk damage due to termite bites started from the bark surface side (mud tubes), e.g. *Odontotermes formosanus* and, thus, causing sap flow, canker or further wood decay.

Odontotermes formosanus was the most frequently encountered species and various

Table 2 Transversal stress wave velocities of undamaged hoop pine trees (group A)

	Diameter of 2D image (cm)	Velocity (m s^{-1})		
		V_{min}	V_{mean}	V_{max}
	28.0	1111	1363	1616
	23.9	1015	1316	1617
	27.4	1174	1436	1699
	31.2	1115	1378	1642
	32.5	1184	1413	1642
	28.3	1235	1501	1768
	28.0	1187	1431	1676
	26.1	1111	1344	1578
	30.9	1222	1556	1891
	30.6	1187	1443	1700
	26.7	1197	1408	1620
	24.2	1110	1343	1576
Average	28.1	1154	1411	1669
	(2.7)	(63)	(69)	(89)

n = 15; V_{min} = minimum stress wave velocity, V_{mean} = mean stress wave velocity, V_{max} = maximum stress wave velocity; standard deviations are given in brackets

Table 3 Inspected measurements of undamaged hoop pine trees by different nondestructive techniques (group A)

	DF (m Hz)	R (%)	C (MPa)	D (kg m^{-3})
	315.1	34.0	26.1	598.9
	340.2	40.7	31.2	579.5
	313.1	32.8	20.5	531.1
	335.3	36.5	25.7	630.1
	330.8	42.0	25.8	562.1
	347.0	55.4	31.7	542.1
	341.4	32.0	25.9	617.6
	318.1	42.7	27.3	679.1
	339.6	30.0	28.4	542.4
	313.2	32.5	26.0	579.1
	327.5	44.4	22.6	529.5
	310.0	53.4	23.7	544.1
Average	327.6	39.7	26.2	578.0
	(13.2)	(8.4)	(3.2)	(46.2)

DF = lateral impact vibration performance, R = drilling resistance value, C = crushing strength, D = density; standard deviations are given in brackets

Table 4 Transversal stress wave velocity in 2D images of undamaged trees (group B)

	Diameter of 2D image (cm)	Velocity (m s^{-1})		
		V_{min}	V_{mean}	V_{max}
	52.5	1298	1648	1998
	53.5	1124	1517	1911
	53.5	1367	1586	1806
	61.1	1221	1547	1874
	61.1	1380	1591	1802
	39.8	1058	1432	1807
	52.5	1222	1522	1822
	57.3	1437	1677	1918
	26.1	1155	1485	1816
	36.6	1368	1618	1868
	43.0	1235	1541	1848
	57.3	1009	1366	1724
	43.0	1235	1718	2202
	39.8	1038	1494	1951
	54.1	1095	1341	1588
	43.0	1080	1417	1755
	37.6	1110	1504	1899
	41.4	1095	1320	1546
	43.0	1085	1376	1668
	52.5	1165	1389	1613
	46.2	1151	1414	1677
	35.0	1237	1543	1850
	51.0	1145	1492	1839
	52.5	1048	1358	1669
	47.8	1080	1301	1522
	44.6	1083	1589	2095
	41.4	1080	1331	1582
	57.3	1001	1373	1746
Average	47.3	1164	1482	1800
	(8.6)	(119)	(116)	(160)

n = 28; V_{min} = minimum stress wave velocity, V_{mean} = mean stress wave velocity, V_{max} = maximum stress wave velocity; standard deviations are given in brackets

shapes of mud tubes were found on the surface or underneath the barks, causing damage in the trunk. In this study, *C. formosanus* and *C. gestroi* were discovered. Mud tubes were observed on the tree barks and trunks of living trees were damaged.

Average transversal stress wave velocity, lateral impact vibration performance, drilling resistance value, green crushing strength and air-dry wood density of normal undamaged tree stem served as diagnosis indices or standard reference values (Tables 2–4). If detected values of nondestructive evaluation were lower than these reference values, wood quality of the trunk could not be assured and required further detection.

In this study, lower transverse stress wave velocities (map grids) were observed inside the termite-damaged tree. Severe wood decay can reduce stress wave velocity up to 70% of the

Table 5 Transversal stress wave velocity in 2D images of termite damaged trees (group C)

	Diameter of 2D image (cm)	Velocity (m s^{-1})		
		V_{min}	V_{mean}	V_{max}
	39.5	990	1780	2570
	51.6	643	1220	1797
	44.6	616	985	1355
	19.1	1005	1233	1462
	43.3	617	1038	1459
	21.0	1021	1289	1557
	39.8	998	1304	1611
	26.4	1022	1373	1724
	36.0	753	1199	1646
	35.0	946	1237	1528
	35.7	841	1318	1796
	34.4	819	1245	1672
	49.4	956	1216	1477
	47.8	861	1247	1633
	24.2	791	1119	1447
	54.1	947	1228	1510
	52.5	937	1228	1520
	57.3	962	1376	1791
Average	39.5	874	1258	1642
	(11.6)	(139)	(164)	(266)

n = 18; V_{min} = minimum stress wave velocity, V_{mean} = mean stress wave velocity, V_{max} = maximum stress wave velocity; standard deviations are given in brackets

characteristic values of sound wood, indicating that decrease of strength is serious (Bethge et al. 1996). In this study, average velocity values in the undamaged trees were 1411–1482 m s^{-1} with threshold values at 988–1038 m s^{-1} (i.e. 1411–1482 × 0.7 m s^{-1}). Minimum velocity values of tomogram in the undamaged trees were 1154–1164 m s^{-1}. Therefore, these values can be considered as the threshold values for diagnosis by stress wave velocity tomogram. The range of demarcation between termite-damaged and undamaged wood occurred at an approximate transversal stress wave velocity of 988–1164 m s^{-1}. The reduction in velocity was indicative of serious damage, the location and extent of which could be seen in the map grids. The termite-damaged tree had lower average and individual stress wave velocities compared with undamaged tree.

Some studies have reported that acoustic tomogram and other techniques for tree risk assessment cannot precisely evaluate the extent and location of decay or the type of defect (Gilbert & Smiley 2004, Wang et al. 2007, 2009, Lin et al. 2011) Acoustical tomogram underestimates internal decay and overestimates decay in the periphery of the trunk. Therefore, to make better assessments of internal conditions and decay of trees, other more effective methods (e.g. visual drawings of the increment core, drilling resistance and use of a fractometer) should also be adopted in combination to enhance the accuracy of the assessment.

In-depth tree assessments are warranted when trees pose high degree of risk to public safety and exhibit defects that cannot be fully evaluated by visual inspection. However, micro-destructive methods can destroy the compartmentalisation zone and break the existing barrier zone within the tree, allowing decay to spread into healthy wood. Therefore, when using decay detection devices, the number of drill holes or sensor sites for collecting the

Figure 4 Failure due to termite damage in a living tree

required critical field data should be kept to a minimum (Wang et al. 2007).

Thicker peripheral region and higher ratio of peripheral wood towards the trunk base have significant implications on tree structure and safety (sound and health). When hoop pine trees have trunk decay, deterioration or hazardous defects, residual wall thickness (shell) and wood quality were found to be marginally sufficient. A ratio between 30 and 35% of sound wood in the remaining wall is the threshold that requires mitigation methods for decrease of risks (Harris et al. 2004, Hayes 2007)

This experiment found abnormal transversal stress wave velocity tomogram in lean hoop pine tree (Figure 3). Maximum velocity value of lean hoop pine trees showed higher velocity value than those of non-lean normal trees. Although the velocity tomogram and corresponding velocity value maps displayed distinct patterns of different velocity values at the cross-section of the stem, there were within-tree variations of velocity values in the cross-section areas of the velocity tomogram and maps. Velocity values of the cross-section were totally (combined action) influenced by distribution of the cell structure, reaction wood and gravity which might limit the ability to use velocity tomogram.

CONCLUSIONS

The purpose of this study was to investigate standard values of living, undamaged hoop pine trees by different nondestructive evaluations. This study also detected stress wave velocity tomogram and resolved corresponding velocity maps of termite-damaged and undamaged hoop pine trees. Average velocities were 1154–1669 and 1164–1800 m s^{-1} for undamaged hoop pine trees. Average lateral impact vibration performance, drilling resistance value, green crushing strength and air-dry wood density were 327.6 m Hz, 39.7%, 26.2 MPa and 578 kg m^{-3} respectively. Minimum velocity values (1154–1164 m s^{-1}) could be considered as threshold values for diagnosis by stress wave velocity tomogram. The range of demarcation between termite-damaged and undamaged wood occurred at approximate transversal stress wave velocity values of 988–1164 m s^{-1}. Different parameters of nondestructive evaluation could serve as indices of the diagnosis values. Transversal stress wave velocity tomogram and corresponding stress wave velocity maps of termite-damaged and undamaged hoop pine trees could detect the general location and area of wood deterioration.

REFERENCES

Bethge K, Mattheck C & Hunger E. 1996. Equipment for detection and evaluation of incipient decay in trees. *Journal of Arboriculture* 20: 13–37.

Gilbert E & Smiley ET. 2004. Picus sonic tomography for the quantification of decay in white oak (*Quercus alba*) and hickory (*Carya* spp.). *Journal of Arboriculture* 30: 277–281.

Harris RW, Clark JR & Matheny NP. 2004. *Arboriculture: Integrated Management of Landscape Trees, Shrubs, and Vines*. Pearson Education, Upper Saddle River.

Hayes E. 2007. *Evaluating Tree Defects, a Field Guide*. Safetrees, Rochester.

Lee HF, Yeh HT, Wang YN & Tsai MJ. 2011. Termite diversity and damage pattern in tropical botanical garden of Taiwan. *Journal Experiment Forest National Taiwan University* 25: 139–147.

Lin CJ, Chang TT, Juan MY & Lin TT. 2011. Detecting deterioration in royal palm (*Roystonea regia*) using ultrasonic tomographic and resistance microdrilling techniques. *Journal of Tropical Forest Science* 23: 260–270.

Lin CJ, Chiu CM & Wang SY. 2000. Application of ultrasound in detecting wood decay in squirrel-damaged standing trees of Luanta China fir. *Taiwan Journal of Forest Science* 15: 267–279.

Lin CJ, Chung CH, Wu ML & Cho CL. 2013. Detection of *Phellinus noxius* decay in *Sterculia foetida* tree. *Journal of Tropical Forest Science* 25: 487–496.

Mattheck C & Breloer H. 1994. Field guide for visual tree assessment (VTA). *Journal of Arboricultural* 18: 1–23.

Pellerin RF & Ross RJ. 2002. *Nondestructive Evaluation of Wood*. Forest Products Society, Madison.

Pokorny JD. 1992. *Urban Tree Risk Management: A Community Guide to Program Design and Implementation*. USDA Forest Service Northeastern Area State and Private Forestry, St. Paul.

Wang X & Allison RB. 2008. Decay detection in red oak trees using a combination of visual inspection, acoustic testing, and resistance microdrilling. *Arboriculture and Urban Forestry* 34: 1–4.

Wang X, Allison RB, Wang L & Ross RJ. 2007. *Acoustic Tomography for Decay Detection in Red Oak Trees*. Research Paper FPL-RP-642. US Department of Agriculture, Madison.

Wang X, Wiedenbeck J & Liang S. 2009. Acoustic tomography for decay detection in black cherry trees. *Wood and Fiber Science* 41: 127–137.