Reliability of non-destructive sonic tomography for detection of defects in old *Zelkova serrata* (Thunb.) Makino trees

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ABSTRACT

*Zelkova serrata* (Thunb.) Makino trees, which account for a large proportion of cultural assets and protected trees and have considerable historical and cultural symbolic meaning in South Korea. To verify the reliability of the nondestructive sonic tomography (SoT) method on *Z. serrata* trees, this study compared the results of SoT with those obtained with the destructive resistance micro-drilling method. With SoT measurement, defects were found in approximately 75% of the target *Z. serrata* trees and two of these trees were evaluated as having a high risk because their defective portions accounted for approximately 70% or more of the entire cross section. The independent samples t-test indicated that the two methods did not show a significant difference between measurements. Regression analysis indicated that the measurement values of the two methods showed a positive relationship with a high explanatory power of 76%, thus, verifying the reliability of SoT.

Introduction

Decay or large-scale cavities in trees are the main cause of trees falling or breaking, and structurally weak trees are vulnerable to strong wind or heavy snow. However, internal defects are difficult to assess using visual inspection only, which makes managing and preparing for relevant risks challenging. With the occurrence of an increasing number of strong winds and typhoons owing to climate change, casualties and financial damage caused by tree fall in cities have also increased. In addition, cultural assets have been damaged.

Methods of diagnosing internal defects in trees can be broadly classified into two classes: destructive methods, such as using increment borers or resistance micro-drilling, and nondestructive methods, such as using acoustic waves or electromagnetic waves. For old trees, especially those designated as cultural assets or protected trees, nondestructive diagnostic methods should be used to minimize physical damage to the trees.

Among the various nondestructive methods, sonic tomography (SoT) can provide information on the entire cross section of a tree and is applicable to old trees. Thus, numerous studies have explored the accuracy and practicality of this method. Since the early 2000s, detailed investigations have been conducted on the applicability of SoT in terms of accuracy, development of more precise measurement methods, and evaluation of deviations in accuracy measurements based on wood rotting fungi, including in tropical regions, for different species of trees such as *Alseis blackiana* and species of *Quercus*, *Acer*, and *Betula*. The accuracy of SoT differs depending on the timber properties of the tree species (Gilbert and Smiley 2004; Rabe et al. 2004; Deflorio et al. 2008; Wang and Allison 2008; Brazee et al. 2011; Tallavo et al. 2012; Gilbert et al. 2016; Karlinasari et al. 2016). However, few studies have been conducted to verify the reliability of this diagnostic method on tree species native to the Korean Peninsula.

This study aimed to analyze the reliability of nondestructive SoT on old *Zelkova serrata* (Thunb.) Makino trees. *Z. serrata* trees are deciduous broad-leaved trees belonging to Ulmaceae and are distributed in the Korean peninsula, China, and Japan. These trees account for 53% of all protected trees designated by the Korea Forest Service. Among the diverse species of trees designated as natural monuments, which are cultural assets selected by the Korean government, *Z. serrata* trees are the second highest in number after *Ginkgo biloba*. *Z. serrata* trees are natural assets that have traditionally existed alongside the Korean people as sacred trees and shade trees placed near gazebos. Thus, it can be said that these trees have high biological value as well as symbolic characteristics related to the culture and history of Korea.

In this study, to verify the reliability of SoT data, a destructive method, resistance micro-drilling (PD-600,
IML, Germany), was used to acquire data for comparison. In resistance micro-drilling, a long, narrow (approximately 3 mm in diameter) drill bit penetrates the timber, during which the resistance decreases as the drill bit passes through defects (cracks, cavities, and decay). Because of its high accuracy, resistance micro-drilling is widely used in decay detection or structural evaluation of timber (Rinn 1990, 2012; Geraldi et al. 2001; Lee and Kim 2003; Lin et al. 2003; Park et al. 2006; Zhang et al. 2009; Acuña et al. 2011; Tokyo Metropolitan Government Bureau 2014; Allison and Wang 2015; Frontini 2017; Karlinasari et al. 2017; Downes et al. 2018; Fundova et al. 2018; Sharapov et al. 2018, 2020).

In this study, the results obtained through performing SoT and resistance micro-drilling on Z. serrata trees were compared to verify the reliability of SoT and to promote the extended application of this non-destructive method in fields related to the diagnosis of these trees. Furthermore, it is expected that the findings of this study will be used effectively to improve preemptive tree management through mid- and long-term monitoring of defects in trees.

Materials and methods

This study examined 200- to 400-year-old protected Zelkova serrata (Thunb.) Makino trees located in Yuseong-gu, Daejeon, South Korea (Figure 1). Twelve Z. serrata trees were inspected through field investigations from July to August 2018. The defects in these trees were diagnosed utilizing the nondestructive SoT method. To verify the reliability of these methods, the results were compared with those of resistance micro-drilling, a destructive method.

For cross-validation, the lengths of internal defects (cm) obtained using resistance micro-drilling and SoT were compared across 42 measurement points (MPs) (Table 1). Independent sample t-test and simple linear regression analysis of the MPs were performed using SPSS 21.0 (IBM Corp., Armonk, NY, USA).

Sonic tomography

The SoT method measures the velocity (transmission time) of acoustic waves in the internal section of a tree, and this varies according to elastic moduli and timber density. As decay and cavities of a tree reduce the elasticity and density of timber, acoustic velocity tends to decrease in these areas in comparison to that in a healthy part (Gilbert et al. 2016). This study utilized the PiCUS 3 Sonic Tomograph (Argus Electronic GmbH, Rostock, Germany) to measure the cross section of the tree trunk at 100 cm above ground level. The PiCUS 3 software visualizes the transmission time of acoustic waves as a two-dimensional sonic tomogram, where brown denotes high velocity corresponding to healthy tissues (high density), red and blue denote low velocity corresponding to defects (decay and cavities), and green denotes initial stages of decay or the transitioning area between healthy and defective portions.

After SoT, for in-depth diagnoses of trees with large defective areas, ERT was additionally performed to deduce the type of internal defects and detect initial decay. ERT measures the water content and electrical resistance of the tree cross-section using current and voltage, and PiCUS 3 Treetronic (Argus Electronic GmbH, Rostock, Germany) was used in this study.

To compute the area of defective portions for each tree from the SoT data, the data were quantified through image analysis using the ImageJ software (National Institutes of Health; http://imagej.nih.gov, open source), which was also used in Gilbert et al. (2016).

Resistance micro-drilling

Resistance micro-drilling (PD-600, IML, Wiesloch, Germany) was performed on 42 MPs suspected of defects based on visual inspections and acoustic wave measurements. The measurements were recorded parallel to the ground, starting from the bark of the tree and pointing toward the center of the tree (in the radial direction).

Results and discussion

Sonic measurement

The area of the defective portion calculated through SoT quantification indicated that the area of the defective part, including cavities and decay, in all trees, except in trees Nos. 4, 7, and 9, exceeded one-third (42.8–83.4%) of the entire section. The largest area of the defective portion was observed in trees Nos. 6 and 10, accounting for 81.3 and 83.4%, respectively (Table 2). In particular, in treesNos. 6, 8, and 10, the area of the defective portion with cavities was estimated to account for 70% or more. As the ratio of residual wall thickness (t) to the radius (r) of a stem was 30% or less, the level of risks was considered to be high in these parts. The t/r of a stem is one of the criteria for evaluating the risk of a tree. If t/r < 0.3 for a full crowed tree exposed to wind loads or if the area of the internal cavity portion accounts for approximately 70% or more, the tree is evaluated as having a
risk of being damaged (Dunster et al. 2013; Mattheck et al. 2015). This theory was first introduced by Mattheck and Breloer (1994) and was applied in a manual for tree risk assessment developed by the International Society of Arboriculture. However, such risk evaluation should be performed thoroughly as Table 1.

Table 1. Results of t-test on lengths of defects measured with sonic tomography (SoT) and resistance micro-drilling (N = 42).

| Tree No. | Measuring length (cm) | Resistance micro-drilling (A) | SoT (B) | Difference (A–B) | Tree No. | Measuring length (cm) | Resistance micro-drilling (A) | SoT (B) | Difference (A–B) |
|----------|-----------------------|-------------------------------|---------|------------------|----------|-----------------------|-------------------------------|---------|------------------|
| 1        | 2                     | 35                            | 32      | 3                | 7        | 4–5                   | 60                            | 4       | 0                |
| 3–4      | 45                    | 22                            | 8       | 14               | 3        | 2                     | 10                            | 2       | 0                |
| 8–9      | 26                    | 24                            | 26      | 2                | 13–14    | 60                    | 0                             | 0       | 0                |
| 13       | 39                    | 15                            | 12      | 3                | 4–5      | 46                    | 0                             | 0       | 0                |
| 19       | 42                    | 21                            | 19      | 2                | 12–13    | 25                    | 12–13                         | 25      | 18               |
| 22       | 58                    | 35                            | 28      | 7                | 1–2      | 53                    | 2                             | 21      | 21               |
| 1–2      | 34                    | 18                            | 34      | 16               | 10–11    | 52                    | 5                             | 0       | 5                |
| 13       | 36                    | 15                            | 15      | 3                | 12–13    | 60                    | 0                             | 0       | 0                |
| 15       | 41                    | 15                            | 11      | 4                | 1        | 60                    | 38                            | 14      | 7                |
| 7        | 48                    | 12                            | 6       | 6                | 3–4      | 31                    | 15                            | 19      | 4                |
| 10       | 54                    | 13                            | 28      | 15               | 5–6      | 35                    | 20                            | 23      | 3                |
| 12       | 52                    | 26                            | 42      | 16               | 16–17    | 39                    | 26                            | 25      | 1                |
| 3        | 7                     | 48                            | 12      | 6                | 3–4      | 31                    | 15                            | 19      | 4                |
| 1        | 57                    | 31                            | 28      | 3                | 10       | 41                    | 31                            | 39      | 8                |
| 9        | 43                    | 16                            | 26      | 10               | 12       | 7                     | 6                             | 5       | 1                |
| 6        | 1                     | 60                            | 60      | 58               | 2        | 8                     | 45                            | 44      | 1                |
| 3–4      | 60                    | 50                            | 46      | 4                | 14       | 46                    | 3                             | 11      | 60               |
| 18       | 60                    | 50                            | 41      | 9                | 18       | 60                    | 51                            | 47      | 4                |

Category | Mean | Standard deviation | t   | p   |
Defect length | Resistance micro-drilling | SoT | Resistance micro-drilling | SoT | 0.066 | .947 |
22.26 cm | 22.02 cm | 16.799 | 16.165 |

Table 2. Defective trees identified using PiCUS and confirmed through resistance drilling.

| Tree no. | Diameter (cm) | Total | Severe | Initial decay | Resistance drilling path (confirmation) |
|----------|---------------|-------|--------|---------------|----------------------------------------|
| 1        | 592           | 73.1  | 64.2   | 8.9           | 2 (o), 3/4 (P—N), 8/9 (o), 13 (o), 19 (o), 22 (o) |
| 2        | 420           | 77.1  | 66.0   | 11.1          | 1–2 (N—P), 13 (o), 15 (o)              |
| 3        | 417           | 42.8  | 31.3   | 11.5          | 7 (o),10 (o), 12 (N—P)                 |
| 4        | 353           | 1.4   | 0.6    | 0.8           | 1/2 (o), 11/12 (o), 6/7 (o)             |
| 5        | 524           | 66.8  | 61.1   | 5.7           | 1 (o), 9 (o), 12/13 (P—N), 13/14 (P—N) |
| 6        | 522           | 81.3  | 69.7   | 11.6          | 1 (o), 3/4 (o), 14 (N—P), 18 (o)       |
| 7        | 380           | 3.2   | 0.6    | 2.6           | 4/5 (o), 6/7 (o), 10/11 (o), 13/14 (o) |
| 8        | 365           | 77.3  | 60.2   | 17.2          | 4/5 (o), 12/13 (o)                      |
| 9        | 530           | 14.1  | 5.6    | 8.5           | 1/2 (N—P), 2 (o), 10/11 (o), 12/13 (o)  |
| 10       | 515           | 83.4  | 69.9   | 13.5          | 1 (N—P), 3/4 (N—P), 5/6 (o), 16/17 (o) |
| 11       | 320           | 66.5  | 55.1   | 11.4          | 2 (N—P), 5 (N—P), 9 (N—P), 10 (o)      |
| 12       | 385           | 60.3  | 43.4   | 17.0          | 7 (o), 8 (o), 11 (o)                    |

o: SoT & resistance profiles matched; N—P: SoT: unsound—resistance profiles sound; P—N: SoT: sound—resistance profiles unsound.

Figure 2. Sonic tomography (SoT) with safety margin and electrical resistance tomography (ERT) tomograms. A (SoT) – B (ERT) = tree no. 6, C (SoT) – D (ERT) = tree no. 10, red dotted lines = safety margin.
Correlation validation is required for trees with a large diameter and results can differ depending on the status of exposure to wind loads, location of decay, and bearing power (Dunster et al. 2013).

In Tree No. 6, which had a relatively large defective portion as well as an open cavity, 81.3% of the entire section of its center where acoustic velocity was comparatively low, was identified as the defective portion and 61.7% of this defective part was diagnosed as severely defective (Figure 2). The ERT result indicated that the central part was estimated to include a cavity or a dead timber portion owing to a low percentage of water content and a high electric resistance value. In tree No. 10, 83.4% of the entire section was analyzed as defective, and 69.9% of the defective part was diagnosed as severely defective. In addition, this tree

| Tree no. | PICUS tomogram | RESISTOGRAPH profile (MP) |
|----------|----------------|---------------------------|
| #1       | ![Image](#)    | ![Image](#)               |
| #2       | ![Image](#)    | ![Image](#)               |
| #3       | ![Image](#)    | ![Image](#)               |
| #4       | ![Image](#)    | ![Image](#)               |

*Figure 3. Sonic tomogram superimposed with the RESISTOGRAPH profile for selected drilling measurement points (MP). In sonic tomograms and resistance profiles graphs, both white and green lines indicate depth of drilling path and sound region, and red lines represent the depth of the decay region. (Refer online version for colored figures.)*
exhibited the lowest $t$ value. The electrical resistance measurement showed that the left side of the defective part was identified as including a cavity or dead timber based on a low percentage of water content. At MPs Nos. 14–17 located on the right side, based on low acoustic velocity and a particularly high percentage of water content, the decay was estimated to be extended along the boundary.

**Comparison of results based on SoT and resistance micro-drilling measurement through cross-validation**

The results of resistance micro-drilling and SoT are presented in Table 2. Resistance micro-drilling was conducted at the 42 MPs identified with SoT to verify the reliability of the results, and an independent samples $t$-test and regression analysis were performed.
The measured lengths of internal defects showed a mean difference of 5.9 cm between SoT and resistance micro-drilling across the 42 MPs. A t-test on the two sets of measurements indicated that SoT and micro-drilling results had a mean of 22.26 cm and 22.02 cm, respectively, with no significant difference found between the two mean values ($t = 0.066, p = 0.947$) (Table 1).

**Figure 3.** Continued.

**Figure 4.** Predicted distance of compromised wood using sonic tomograph versus distance of defects using the IML-Resistograph. Trend line = linear regression. $p = 0.001, r^2 = 0.764, n = 42$. 
In detail, Figure 3 shows both the results of SoT and resistance micro-drilling. The red line indicates the depth of internal defects (e.g. decay and cavities). Inconsistencies were observed in certain parts of 10 among the 42 MPs. Examination of these inconsistent parts indicated that those portions estimated to be initial decay (green) or transition areas in the SoT results were diagnosed as healthy portions according to the micro-drilling resistance results. The drilling resistance method failed to detect mold which invaded the initial decay portion because the cell wall remained healthy and might not have affected timber strength. In terms of errors, the ratio of errors can increase when the types of defects (e.g. decay, cracks, and cavities) in a tree are complex, when several cracks are generated in the tree, or when such cracks are round and occur along the edge (Gilbert et al. 2016).

A regression analysis was performed to investigate the correlation between the two sets of measurements. The resulting model showed statistical significance, with 76% of the variance being explained ($F = 129.526$, $p < 0.001$, $R^2 = 0.764$). The lengths obtained through SoT and resistance micro-drilling showed a significant positive correlation; as the defect size identified with SoT increased, the defect size identified with resistance micro-drilling also increased (Figure 4). This indicates
that SoT is a reliable diagnostic method that can be used to perform measurements of *Z. serrata* (Thunb.) Makino trees.

The results were also consistent with those obtained with the visual inspection. Nondestructive testing showed that trees Nos. 1, 3, and 6 had low acoustic velocity, a low percentage of water content, and high electrical resistance. This indicated that these trees were estimated to include internal cavities, which was consistent with the results mentioned above (Figure 5).

**Conclusions**

In this study, *Zelkova serrata* (Thunb.) Makino trees designated as protected trees in South Korea were diagnosed using the nondestructive SoT and ERT methods. Defects were observed in 75% of trees; defective parts, including cavities, in five trees accounted for 70% or more of the entire section. Two of the five trees were evaluated to have a high risk because the severely defective parts, excluding initial decay, accounted for approximately 70% of the entire section.

The result obtained on the nondestructive SoT method was compared with that obtained based on the destructive resistance micro-drilling method and it was verified that the mean values between the two methods did not show a significant difference. Moreover, the degree of damage estimated based on SoT showed a significant positive relationship with that estimated based on resistance values from micro-drilling, thereby confirming the reliability of SoT. This confirmed that SoT could be used as a nondestructive investigative method for internal defects in *Z. serrata*, designated as natural monuments. The SoT is an effective method for preemptive tree management in that it facilitates mid- and long-term monitoring of changes in internal decay and cavities of trees, which cannot be diagnosed through visual inspection, with minimum damage to the trees. However, the accuracy can vary according to the characteristics of tree species. Further research should be conducted on main tree species of the Korean Peninsula.

**Disclosure statement**

No potential conflict of interest was reported by the author(s).

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