Coarse root distribution of *Vatica pauciflora* (Korth.) Blume in different soil slopes as revealed by root detector

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Abstract. Tree roots have an essential role in absorbing water and nutrients from the soil and supporting tree stability. As an anchor for the tree, the environment can significantly affect root structure but it is rarely investigated due to below ground distribution. The study was aimed to determine the distribution of coarse roots of *Vatica* trees (*Vatica pauciflora*) which grows in different soil slopes. Six mature *Vatica* trees at Bogor Botanical Garden were selected in this study. Root detector as the main tool based on acoustic method was used to evaluate the root distribution. Analysis photogrammetry was carried out to complement the root detector results. The results found that the root detector only can evaluate the radial distribution of coarse root, while root distribution on downward soil cannot be detected. The condition of the site with different slope categories (e.g., flat to steep) affected root distribution patterns. A study on root distribution was useful to assist the evaluation of tree stability and to support arboriculture study.

1. Introduction

Root system morphology is a complex system with high variation. Root morphology is influenced by tree species, soil type, and growing conditions [1]. The stability and dispersion of roots in flat soil locations are different from trees growing in steep soil category. In the field, the slope is a complex environmental situation that exposes plants to various mechanical stressors, including the turning moment caused by the combination of the inclination and the stem and soil slope category. The mechanical forces caused by their static loading will affect the root architecture, especially the direction of root growth and distribution, to avoid uprooting [2, 3, 4].

Root architecture is a horizontal and vertical root distribution that significantly affects tree stability [5]. Tree stability is also influenced by several factors such as tree nutrition, ability to distribute roots in the soil, the mechanical strength of roots [6, 7], physical and mechanical properties of soil [8], depth and shape of the roots [1] and depend on the trunk-root interaction [9]. Research on the effect of slope on root development has been carried out [2, 3, 4]. Most of the research is carried out by excavating the soil and then doing root mapping and measuring the biomass of the roots of a tree. Excavating was used...
due to the roots growing below the soil surface. Tools and techniques were developed in determining the roots to avoid excavating, which impacted the trees. Several studies on root architecture and distribution have begun to use non-destructive testing techniques such as using ground-penetrating radar (GPR) [10], electrical impedance tomography (EIT) [11], and X-ray computed tomography [14]. However, there are still many challenges in its use; for example, the use of GPR is limited to urban environments because it cannot distinguish roots from utility lines (gas and water pipes) [15] and is not effective in soils with high clay and water content [14]. In addition, these techniques are still costly; thus, there is no efficient and inexpensive non-destructive testing tool that can map the root system or detect the presence of large individual roots [17].

A root detector is a new alternative in detecting the presence of roots. The tool uses the principle of sonic tree tomography by utilizing different time-of-flight of waves as they pass through roots and soil. At least some research on the use of these principles and methods for detecting coarse roots in the soil has been conducted [5, 16, 17]. However, the research is still limited to trees with small diameters and flat growing conditions. Therefore, in this study, the *Vatica pauciflora* (Korth.) Blume tree was selected, belonging to the collection of the Bogor Botanical Gardens (BBG) which is categorized as a big and old tree/conserved cultural heritage because of its VU-Vulnerable status regarding the IUCN (International Union for Conservation of Nature) Red List of Threatened Species [12]. This study also uses photogrammetry to see the image of the roots above the ground as an indication of the presence of roots; this is useful if the test is carried out on special properties that should not be disturbed. This study was aimed to determine the distribution of coarse roots in variations of soil slope using root detectors tool on the Vatica trees.

2. Method

2.1. Sampling and site description

The research was carried out on six *Vatica pauciflora* (Korth.) Blume trees spread at the Bogor Botanical Garden (figure 1) for the period of April to June 2021. Bogor Botanical Garden (BBG) located at central of Bogor city area that has a tropical climate with an altitude of 231-270 m asl with an average rainfall of 3.712 mm/year and temperature about 20.1 to 29.4°C with humidity in a range of 35 to 99% [13]. Six old and large trees of more than 50 years old were selected by purposive sampling (table 1). Different tree position based on the soil slope was considered in this study (figures 2). The two slopes used were plane or flat (<2°) and sloping (>15°) according to the SOTER classification [20].

figure 1. Location of *Vatica pauciflora* trees
Vatica tree no 1 (a)  Vatica tree no 2 (b)  Vatica tree no 3 (c)

Vatica tree no 4 (d)  Vatica tree no 5 (e)  Vatica tree no 6 (f)

**Figure 2.** *Vatica pauciflora* trees samples: (a), (b), (c) on flat soil; (d), (e), (f) on moderately steep soil.

| No | Tree                  | Diameter (cm) | Height (m) | Age\(^a\) | Soil          |
|----|-----------------------|---------------|------------|-----------|---------------|
| 1  | Vatica tree no 1      | 54.5          | 14         | 61        | Flat          |
| 2  | Vatica tree no 2      | 72.0          | 16         | 61        | Flat          |
| 3  | Vatica tree no 3      | 47.5          | 15         | 61        | Flat          |
| 4  | Vatica tree no 4      | 63.0          | 14         | 105       | Moderately steep |
| 5  | Vatica tree no 5      | 102.0         | 18         | 105       | Moderately steep |
| 6  | Vatica tree no 6      | 45.0          | 15         | 105       | Moderately steep |

\(^a\) Internal data from BBG

### 2.2. Photogrammetry analysis

The photogrammetry method was used to map the distribution of roots visually. This method usually is commonly developed by modeling approaches based on aerial capture method. The information is then extracted through interpretation of aerial photographs [21, 22, 23]. The simple photogrammetric method through capture picture by a cell phone camera was used in this study. Each tree was taken at least 30 photos to get a fairly clear picture of root distribution above the ground up to the tree stump, as well as the slope soil capturing. The photos obtained were then processed using open-source software, COLMAP. COLMAP is a general-purpose Structure-from-Motion (SfM) and Multi-View Stereo (MVS) pipeline. SfM is the process of reconstructing 3D structure from its projections into a series of images.
taken from different viewpoints [24] (figure 3). For finalized the image data was conducted by Meshlab software. Analysis data of photogrammetry can be used to calculate prediction of the site slope.

![Figure 3](image-url)

**Figure 3.** Example appearance of Structure-from-Motion (SfM) process using COLMAP on Vatica tree no 1: (a) point of view from transverse, (b) point of view from the side.

2.3. **Root detection**

Fakopp® Root Detector tool was used to estimate the root radial distribution. This method is based on the time-of-flight (ToF) of sound propagation [5, 19]. The tool comprised a piezo sensor with spike as the transmitter, a soil sensor of high-frequency geophone with spike as the receiver, and a time-measuring component. The transmitter sensor with spike as the tapping point was inserted on the trunk at the root collar near the ground, while the receiver sensor with spike was inserted into the soil where the root appears above the ground at a certain distance from the main trunk (figure 4a). Both sensors were placed in about 45° position. The principle of root detection based on the acoustic signal’s velocity difference between the root and the soil in which the signal travels through the wood material. The transmitter sensor with spike was hit to generate the sound propagation, and the sound will travel until the receiver sensor. The root detector tool can detect the existence of the roots through sound propagation time in the soil. The traveling time of the signal decrease significantly when the roots were detected nearby the tool in less than 10 cm [19].

The measure was performed along a circle around the trunk at a distance of 100 and 200 cm from the midpoint of the main trunk (figure 4b). Previous study by [4, 5] mentioned that the maximum radial distance for root detection was approximately 6-8-fold the DBH since about this distance the root system biomass was generally found. The test was carried out from the starting point in the north direction, then the in-line pair of sender and receiver sensors, which was limited by a rope, were moved simultaneously with a step of every 15 cm in a clockwise direction up to 360°. A rope was used to maintain a constant distance between the transmitter sensor in the tree and the receiver in the soil (figure 4a). There were 42 data from 100 cm circle and 82 data from 200 cm. In total, it was obtained 124 data for each tree. Measurements at each point were repeated three times. The data was then recorded with the Root Detector Evaluation Software (Fakopp Enterprise Bt, Hungary).
2.4. Root architecture analysis
Root architecture cannot be determined visually in a certain model as a circular, elliptical, or irregular geometry in cross-section. The Root Detector tries to construct the model of root architecture based on the acoustic signal. The time-of-flight (ToF) of sound propagation was converted as sound velocity by dividing the distance of the sensors to ToF. The physical background of the measurement is the velocity-difference in wood and soil. The sound velocity in soil is about 250 to 4000 ms\(^{-1}\), while the sound velocity reference of the roots was in a range of 2000 to 4000 ms\(^{-1}\). Those values were influenced by the environment, including humidity soil type [19, 25]. The root system architecture model was developed using Microsoft Excel 2019 (Microsoft Office, USA) based on the mean value of the maximum and minimum sound velocities referred to [5].

3. Results and discussions

3.1. Root mapping by photogrammetry
The visual surface of above the ground from the six sample trees could be captured by photogrammetry properly and it was sufficient to estimate the existence of the roots above the ground. The information about the direction of the roots above the ground, the visual slope of the soil, as well as the base of the stem were important for validating the root detector tool results related to root direction and distribution. The analysis of photogrammetry can result the estimate the degree of slope. Based on the results of the portrait, it was found that the distribution of the roots of the Vatica tree no 1 (figure 5), Vatica 2 (figure 6), and Vatica 3 (figure 7) trees on the flat-soil had a fairly symmetrical distribution of roots. Meanwhile, the Vatica tree no 4 (figure 8), Vatica 5 (figure 9), and Vatica 6 (figure 10) trees demonstrated that the roots (roots above ground level) tend to point down-slope, but some are also up-slope. The slope degree of Vatica tree no 4, Vatica 5, and Vatica 6 were 30\(^{\circ}\), 25\(^{\circ}\), 18\(^{\circ}\), respectively.

The limitation of photogrammetry method was that it cannot fully describe the distribution of the roots since the main roots below the soil could not be detected. However, this method was useful to give a picture about radial root distribution when the excavation method could not possible to use. The environmental soil condition was also affected on the result of the image when the environment around the tree covered by ground covers or understory. It can lead to decrease in the accuracy of the image. Therefore, weeding and clearing the soil surface will improve image quality.
Figure 5. Root distribution of Vatica no 1 with (a) transverse view; (b) side view less than 2° slope degree.

Figure 6. Root distribution of Vatica no 2 with (a) transverse view; (b) side view less than 2° slope degree.

Figure 7. Root distribution of Vatica no 3 with (a) transverse view; (b) side view less than 2° slope degree.

Figure 8. Root distribution of Vatica no 4 with (a) transverse view; (b) side view 30° slope degree.
3.2. Root detection

The Root Detector tool has revealed the sound velocities of the radial distribution of coarse roots. Except for the Vatica tree no 5, the Vatica no 4 and Vatica no 6 in slope soil site had the lower average speed sound value of 529.48 ms\(^{-1}\) and 605.38 ms\(^{-1}\), respectively, compared with Vatica tree in flat site (figure 11). The Vatica tree no 1, 2, and 3, grown in a flat soil site, possessed the radial distribution root’s sound velocities of 829.97 ms\(^{-1}\), 892.69 ms\(^{-1}\), and 934.37 ms\(^{-1}\), respectively. The Vatica tree no 5 (figure 11), grown in the moderately steep soil site, had the highest value of 1467.22 ms\(^{-1}\). In contrast to the other two trees that grow on moderately steep, figures 2e and 9 confirm the dominant coarse root structure on Vatica tree no 5. It seemed that this related to the tree's ability to respond to the site condition through appearing many coarse roots structure as wood material above the ground. As a result, actual measurements were made on the wood material of the root.
Figure 11. Box plot of the distribution of the sound velocity (ms\(^{-1}\)) detected by root detector at the different slope category. (Notes: circles indicate outlier values, an asterisk indicates extreme value, the different letter points out a significant difference of velocity value).

The sonic velocity values decreased along with the increasing of distance from the trunk, especially on flat soil site (figure 12). Study by [5] mentioned that the limitation of Root Detector revealed when it used for detecting radial root distribution was far from the main tree’s stem. Our study found that in the distance of 200 cm from main trunk had larger standard deviation compared with the distance of 100 cm (figure 2). It can be explained that variation values becoming higher in the longer distance. Furthermore, based on measurement experience in the field, a distance of 200 cm was the maximum distance from the Root Detector, more than that, the tool cannot generate the time-of-flight.
3.3. Root distribution

Root detector has demonstrated the radial distribution of the roots for the six *Vatica pauciflora* trees. The *Vatica* tree no 1, *Vatica* 2, and *Vatica* 3, grown at the flat soil (figure 13, 14, 15), revealed the symmetrical pattern compared to the distribution of roots with slope soil site (figure 16, 17, 18). According to Chiatante et al. [3], trees that grow on a flat soil site will form a "symmetrical bell-shape," while those that grow on slope soil site will form a "bilateral fan-shape." The symmetrical bell-shaped architecture develops from lateral roots growing symmetrically around the taproot. In contrast, the bilateral fan-shaped architecture results from lateral roots growing mostly in the up-or down-slope direction.

Figures 13, 14, and 15 show that the root distribution tends to be symmetric; however, it is not completely symmetric. It seemed that the root distribution affected by other parameters could be affected such as climatic, altitudinal trends [26, 27], edaphic, water and nutrient availability in soil [28], soil texture and compaction level [26], and topographic, the presence of physical obstructions such as stones [30, 31] and the interactions between trees and understorey species [32, 33].

![Box plot of the distribution of the velocity (ms⁻¹) detected by root detector at different distances from the trunk (100 and 200 cm). (Notes: circles indicate outlier values).](image-url)
**Figure 13.** Root distribution Vatica tree no 1 based on the velocity of waves (flat soil) (See Fig. 5).

**Figure 14.** Root distribution Vatica tree no 2 on the velocity of waves (flat soil) (See Fig. 6).

**Figure 15.** Root distribution Vatica tree no 3 on the velocity of waves (flat soil) (See Fig. 7).

**Figure 16.** Root distribution Vatica tree no 4 on the velocity of waves (moderately steep soil) (See Fig. 8).
Based on figures 16, 17, and 18, the root distribution tended to be asymmetrical and had a higher sound velocity in the downslope area, indicating that the root is shallower. Coutts and Nicoll [34] mentioned that the roots grow out of the soil on the downhill side of a steep slope to prevent the death caused by desiccation. The tree, through the roots, should develop its growth orientation and lateral root on up-slope and form the negative gravitropic growth [35]. In this development condition, the up-slope roots’ resistance to pull-out and shear stress may become the most important component of tree anchoring from a biomechanical standpoint [4]. As a result, on a steep slope, the best architecture may be an increase in total root cross-section and a shift in the center of mass (asymmetry indicator). Further investigation is needed to observe the effect of environmental influences such as variations in moisture content and soil density and characteristic of the wood mass density of the root.

4. Conclusion

The radial distribution of coarse roots in different soil slope category can be depicted by root detector tool for six Vatica trees, while the vertical root distribution down into the soil could not be determined. The photogrammetry to complement and clarify the tool’s result has potential to be used for mapping the radial root distribution and calculating the soil slope. Both photogrammetry and root detectors have limitations in determining the root distribution downwards into the soil. The root distribution evaluation was determined based on sound velocities, from which those values were found higher in flat soil site than moderately steep soil. This study can be useful to support the evaluation of the tree stability roots, especially for the tree with shallow roots within the context of arboriculture in urban forests.

5. References

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Acknowledgments

This research was funded by the Indonesia Ministry of Research and Technology (RISTEK)/National Research and Innovation Agency (BRIN) through Research Grants, FY 2021 (contract number: 8/E1/KPT/2021 and 1/E1/KP.PTNBH/2021).