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Impact of Root Distribution Characteristics on the Overturning Resistance of *Leucaena leucocephala* Forest in Debris-Flow Accumulation Area, Dawazi Gully, Yunnan, China

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Abstract: Tree resistance to overturning is crucial in forestry hazard applications and management. Tree anchorage varies considerably with species, tree age, and site conditions. We investigate the relationship between the root characteristics of the overturning slip surface and the role of roots (regarding different diameters in overturning). Four *Leucaena leucocephala* were fully excavated by a quadrate monolith to establish root distribution characteristics, and 19 *L. leucocephala* were uprooted until the trees completely overturned to measure the anchoring resistance to overturning. A model was developed to improve the descriptions of root characteristics in the mechanical processes for tree overturning. The results show that the distribution characteristics of the root system were well described by the model. For the root–soil plate radius, the thickest root diameter and the root biomass of different diameters at the overturning slip surface increased with the diameter at the breast height. The root biomass affected the strength of the overturning slip surface; the root density may be a key factor in identifying the location of the overturning slip surface. The model could predict the overturning moment of most overturned trees; although it overestimated the overturning moment for small diameters at breast height trees, the results will be useful for understanding the influence of root distribution characteristics in overturning.

Keywords: debris flow; overturning model; root distribution characteristic; root reinforcement; critical turning moment

1. Introduction

Forests play an important role in preventing tsunamis, debris flow, rockfall, and snow avalanche hazards [1–4]. However, many forests have also been destroyed by disasters. Storm Klaus, which hit southern Europe in January 2009, resulted in an estimated 43 million m$^3$ of timber being blown down in southwestern France, including 37 million m$^3$ of pine trees [5]. The tsunami caused by the Great East Japan Earthquake on 11 March 2011 caused catastrophic damage to coastal forests in the Tohoku and Kanto regions of Japan [6]. To better assess forests as part of disaster mitigation measures and their resistance to hazards, it is necessary to conduct a valid assessment of the factors affecting the anchorage capacity of trees.

On the one hand, tree overturning resistance is usually influenced by external forces; different hazards affect trees in different ways [7], such as wind, rockfall, avalanche, etc., mainly by applying a direct external force on the above-ground part of the tree to make the tree overturned [8–10]. On the other hand, tree resistance is also influenced by external environments. Rahardjo, et al. [11] suggested that the shear strength of the soil increased when the soil was mixed with granite fragments. Tanaka and Yagisawa [12]...
considered dimensionless shear stress to be an important parameter influencing tree toppling. Kamimura, et al. [13] found that the water content below the root plate significantly affected the root anchorage, the maximum bending moment, the rod angle at maximum force, and the stiffness index. In addition to the characteristics of the trees, some scholars believe that soil properties play an important role in anchorage capacity. Some studies have also demonstrated the role of soil moisture content on tree stability. Défossez, et al. [14] proposed a new model for tree anchorage and simulations and showed that the anchorage of young pines in sandy soils did not decrease sharply with soil wetting until the soil was fully saturated, while the loss of anchorage resistance at full saturation may significantly increase the risk of wind damage to forests grown in sandy soils. Even the position of the tree in the stand and the temperature can affect the anchorage stability of the tree [15]. Meanwhile, hazards, such as floods and debris flow, may also seriously indirectly affect the stability of trees by erosion of the root–soil plates while exerting external forces [16,17]; therefore, studying tree stability requires understanding the root distribution characteristics that affect the root–soil plate size.

The relationship between different tree characteristics and their tree overturning resistance has been investigated by several authors [18–23]. Several studies have shown that aboveground traits, such as stem diameter at breast height (DBH), tree height, and stem volume or weight, are closely related to the critical turning moments of several tree species [24–26]. Sagi, et al. [27] used data from root strain gauges to analyze the influence of the change of the strain and deflection profiles of the root on the bending moment during overturning. The structure of the root system was measured by digitizing the root system in 3D and analyzing the contribution of specific root systems in overturning [28–30]. The finite element method was used to analyze the role of the root system in tree anchoring under different root forms. The tree uprooting process was simulated in two dimensions, and the stress distribution in the soil and root system was estimated during the overturning [31,32]. Some researchers even explained the overturning resistance of the mature tree through the centrifuge modeling method aided by 3D printing techniques [33]. They provided a way to distinguish between the effects caused by root structures and those caused by soil resistance, making it easier to visualize the factors that influence overturning. However, few studies have focused on the relationship between the root characteristics and the overturning slip surface.

However, recent studies have assumed that the size of the root–soil plate was under ideal conditions, which ignores the role played by root characteristics in overturning [34,35]. Some hazards may break the root–soil plates and, thus, reduce the stability of trees, to better understand the influence of root distribution characteristics on tree stability. In this paper, the root distribution characteristics and critical overturning moment of Leucaena leucocephala were analyzed through experiments in the field, and the root characteristics that influence the location of the overturning slip surface and the role of roots of different diameters in overturning are discussed. We propose a new model to improve the description of root characteristics of the mechanical processes for tree overturning, and the results will be useful for understanding the influence of root distribution characteristics on tree overturning resistance.

2. Materials and Methods

2.1. Study Area

The Dawazi Gully is a branch of the Jiangjia Gully located in Yunnan Province, China (26°14′45″ N, 103°06′08″ E) (Figure 1). The watershed covers an area of 2.33 km², the main channel is 2.01 km long, the highest elevation is 2180 m, and the mouth of the gully is 1310 m, with a relative height difference of 870 m. The climate of the Dawazi Gully is distinct between the dry and rainy seasons, with a clear vertical climate zone. The rainy season is from May to October and accounts for more than 85% of the annual rainfall.
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Figure 1. Location of the Dawazi Gully.

The debris-flow scale in the Dawazi Gully is small, generally with a maximum flow rate of 100 m$^3$/s or less, and the duration is generally short, mostly within 30 min, with a capacity of 1.5–1.9 g/cm$^3$. On the morning of 16 June 1994, one of the largest viscous debris flows occurred in the Dawazi Gully and lasted more than 20 min; this hazard was triggered by rainfall from 06:05 to 06:23, with a total rainfall of 10.5 mm for the whole process [36,37].

With the introduction of *Leucaena leucocephala* in recent years to control debris-flow hazards, the debris-flow scale and frequency have decreased in recent decades and the debris-flow accumulation area has been covered by the *L. leucocephala* forest.

2.2. Plant Species and Soil Attributes

The samples used in this study were taken from the *L. leucocephala* forest at the mouth of the Dawazi Gully, which grows in the debris-flow accumulation area and is disturbed by the debris flow hazard during growth; it serves to hold the soil in the debris-flow accumulation area and weaken the debris-flow outflow hazard. These forests are hazard-protective forests formed with some human intervention.

Field experiments and root samples were obtained during July–September 2021, a period of high precipitation, which caused debris-flow hazards; the data can better explain the overturning behaviors of trees in debris-flow hazards. Four *L. leucocephala* individuals with different diameters at breast height (DBH) were selected for the study, and their root distribution characteristics, DBH, underground root biomass ($m_b$), and the slope angle ($\theta$), where the trees grown were measured by the quadrate monolith method. All samples that were chosen were healthy and had few other plants in the immediate area to minimize the influence of other plants [38,39]. The sample characteristics are shown in Table 1.
Table 1. Four *Leucaena leucocephala* with different DBH.

|                | A1    | A2    | A3    | A4    |
|----------------|-------|-------|-------|-------|
| Diameter at breast height \(d_b\) (cm) | 10.01 | 14.64 | 19.41 | 26.78 |
| Underground root biomass \(m_b\) (g)   | 3964.53 | 11,269.36 | 19,250.32 | 46,565.54 |
| Slope angle \(\theta\) (°)              | 9.3   | 8.7   | 12.4  | 10.2  |

The soil of the debris-flow accumulation area where the forest grows was also sampled. The soil of the experimental site was characterized by its particle size distribution (Figure 2). The debris-flow deposit soil consists mainly of gravel and sand, with gravel, sand, silt, and clay grains accounting for 75.1%, 22.6%, 1.9%, and 0.4% of the total mass, respectively. The soil samples were extremely unevenly graded and poorly sorted, while boulders of 10–20 cm in diameter were excavated occasionally during the sampling, which was carried by the debris flow. The dry unit weight of the soil was 1.59 g/cm³, the cohesion \(c\) and the friction angle \(\phi\) of the soil at the site were 2.45 kPa and 31.1°, respectively, by conducting direct shear tests under consolidated drained conditions [40]. Table 2 lists the properties of the soil at the experimental site.

![Figure 2. The soil particle distribution curve at the site.](image)

Table 2. Basic parameters of the deposited soil.

| Gravel 60–2 mm (%) | Sand 2–0.075 mm (%) | Silt 0.075–0.005 (%) | Clay <0.005 (%) | \(\phi\) (°) | \(c\) (kPa) | Unit Weight (g/cm³) |
|-------------------|---------------------|----------------------|-----------------|-------------|-------------|---------------------|
| 75.1              | 22.6                | 1.9                  | 0.4             | 31.1        | 2.45        | 1.59                |

2.3. Measurement of Root Distribution Characteristics

To better analyze the influence of root distribution characteristics on overturning, root distribution characteristics are described through the relationship between the root biomass, root cross-sectional area ratio (RAR), root density (RD), root diameter with DBH, and radial distance of different diameter roots, and all samples were fully excavated by the quadrat monolith method excavation [41,42]. The base of the plant was the origin of coordinates (Figure 3), and samples were collected 20 cm from the base of the plant in the up-slope (U), horizontal-slope (L), and down-slope (D) directions, with each sample measuring 20 × 20 × 20 cm. Each slope was collected horizontally and vertically at the distance of 1.2 m. Five samples of 40 × 40 × 20 cm were also taken directly below the base (O), with a total of 80 samples taken from each plant. All soil and root samples were collected from the samples, the roots were separated and collected by washing, and dried...
in an oven at a constant temperature of 60 °C; the average diameter and biomass of each root were recorded.

Figure 3. (a) The quadrate monolith method excavation (length of each sample side was 20 cm for U, L, and D. The length and width of the D sample were 40 cm, and the depth was 20 cm), (b) before excavation and (c) during excavation.

The relationship between forest tree biomass and tree DBH has been studied by many scholars [43], and it is usually based on an allometry equation that fits the root biomass to tree DBH:

\[ m_b = a_1 d_b^{b_1} \]  

where \( m_b \) is the underground root biomass, \( d_b \) is the diameter at breast height (DBH), and \( a_1, b_1 \) are empirical coefficients. The root mass distribution has been extensively studied and is considered in accordance with the asymptotic equation [43]:

\[ Y = 1 - \beta^r \]  

where \( Y \) is the cumulative fraction of root biomass from the soil surface to depth or horizontal distance \( r \) (between 0 and 100%), and \( \beta \) is the root attenuation coefficient; when \( \beta \) tends to be close to 1, it means that a larger proportion of roots are located away from the stem, while lower values of \( \beta \) assume that the roots are mostly in the soil close to the center of the stem. The cumulative fraction of the root biomass of the four sampled plants with different DBH values was fitted with the soil horizontal, depth, and radial relationship, and the root biomass at a certain distance of different DBH trees from the root system can be calculated.
Considering the different root diameters played by coarse and fine roots in overturning, roots were classified by fine roots (<10 mm) and coarse roots (>10 mm) [44]. The root length, mean diameter, and biomass of each thick root were recorded, and according to Leonardo’s rule, the root diameter of a tree is usually a function of its DBH [45,46]. The distribution characteristics of the root system of a tree are determined early in its growth and do not change with age and DBH [43], the relationship between the thickest root diameter (D) and DBH and distance r was established as follows:

\[ D = f(r, d_b) \]  

(3)

Fine roots were simplified and classified in 10 ranks \( D_i \) from 0 to 10 mm per 1 mm, which were denoted by \( D_1, D_2 \ldots D_{10} \), respectively, where \( D_i = i - 0.5 \) mm, and the biomass \( (M_i) \) of each diameter rank was recorded. The average of the biomass of 10 roots (20 cm long from each diameter rank) was taken as the standard root mass \( (m_i) \) of each rank, and the obtained root samples of that diameter class were equated into the number \( n_i \) of standard roots by \( M_i / m_i \), The RAR of each sample was calculated by

\[ \sum n_i \pi D_i^2 / A_i \]  

(4)

and the RD of each sample was calculated by \( M_i / v_i \), where \( A_i \) is the vertical projection area of the sample and \( v_i \) is the volume of the root–soil sample.

Tree overturning resistance usually depends on the spatial location of the tree’s overturning slip surface, which affects the root–soil plate radius \( r_f \) and the root characteristics [14,24,47]. Recent studies have seen \( r_f \) only as a function of DBH, which neglects the effect of roots. To clearly understand the factors that control the \( r_f \), the thickest root diameter (D), and the root biomass of different diameters, RAR and RD were analyzed.

### 2.4. Field Data for the Tree’s Resistance to Overturning

To simulate the impact of debris flows on a tree by pulling experiments, trees in the downslope direction were used as anchor stakes [48]. For the measured tensile force to be the only external force on the tree when overturning, parts of selected trees above 1.5 m were removed to reduce the effect of crown weight. A traction steel cable was fixed at the stump height \( L = 1.5 \) m and connected to a tension transducer (HANDIP HP-50 KN, China) to measure the force \( (F) \) during overturning. The rotation angle \( \alpha_r \) and the stem rotation angle \( \alpha' \) at the critical moment of overturning were extracted with an HD camera (Figure 4). The tension transducer and tiltmeters were connected to a computer that recorded the data. The tree was pulled with a constant displacement of 0.4 m/min until the tree was completely overturned.

The measuring stakes were arranged on the extension line of the front and rear of the tree trunk, with the stump as the center at 10 cm of each stake interval, and the soil movement on the root plate during overturning was monitored by HD cameras [49]. The angle of tension \( (\theta) \), the root–soil plate radius \( (r_f) \), and the root–soil plate displacement were obtained, and the soil near the overturning slip surface was collected after the experiment, where the root–soil plate displacement \( (l_r) \) was calculated through

\[ l_r = r_f \alpha_r \pi / 180^\circ \]  

(5)
Figure 4. (a) Schematic diagram and mechanical model of the overturning. (Pulling force \( F \), root–soil plate radius \( r_f \), tension angle \( \theta \), slope angle \( \psi \), rotation angle \( \alpha_r \), and the stem rotation angle \( \alpha' \)), (b) before pulling experiments, and (c) the root–soil plate after pulling experiments.

The diameter, location, and number of roots broken and pulled out on the overturning slip surface were also recorded. All chosen samples were healthy and had few other plants in the immediate area to minimize the influence of the other plant root systems. The plants were artificially watered 10.5 mm within 18 min before the experiments to ensure that the soil was close to saturation in the nature condition to simulate tree stability under precipitation conditions of debris-flow hazards in 1994 [13]. The overturning moment \( (M_e) \) applied to the tree by the winch can be calculated [14]:

\[
M_e = FL(\cos(\theta + \varphi) \cos \alpha' + \sin(\theta + \varphi) \sin \alpha')
\]

The tensile strength of the root system was measured to characterize the role played by different diameter roots in overturning. Root tensile samples were selected uniformly with a 10 mm gauge length, epoxy resin was applied at both ends to increase friction before the tensile experiment [50], the roots were moved at a constant speed of 1 mm/s, and tensile force was applied to them. Only samples that broke in the middle third of the root length
between the clamps were considered successful, and the root fracture was due to the force exerted by the tensile force and not caused by structural damage or stress concentration in the root system in the vicinity of the clamp.

When a root system broke in the middle, the diameter of the fracture point on both sides was measured with calipers. Mechanically, the tensile strength ($T_r$) of a root system depends on Young’s modulus and the root diameter. Numerous data indicate that the tensile strength ($T_r$) is proportional to the root diameter ($d_r$) to some power, namely:

$$T_r = a_2d_r^{b_2}$$

where $a_2$ is the scale factor and $b_2$ is the intensity decay rate. The empirical constants vary from tree species to tree species, and these constants play an important role when comparing the tensile strength of different tree species.

2.5. Model for the Tree’s Resistance to Overturning

The purpose of this section is to describe the tree’s resistance to overturning with a model that accounts for the distribution characteristics of the root system and the effect of roots of different diameters on overturning.

This model was based on the overturning process observed in field surveys and experiments [47], where trees tended to form a large root–soil plate [51], the shape of which usually depended on the species and root system architecture [34,44]. The shape of the root–soil plate observed in this experiment tended to be hemispherical, and the coarse roots usually showed being pulled out and fine roots being broken at the overturning slip surface of the root–soil plate. Considering that the overturning resistance moment of the tree was provided by two components, which were provided by the shear force of the root–soil plate and the coarse root anchorage force [52]. Considering that the root–soil plate presented a hemisphere when the tree overturned, assuming that the weight of the tree was dispersed on the overturning slip surface with the angle of internal friction and the center of the hemisphere is the center of rotation of the stump (Figure 5). The overturning slip surface area of a spherical crown with the radius of the root–soil plate radius ($r_f$) and the angle of the friction angle ($\varphi$) is as follows:

$$S_0 = 2\pi r_f^2(1 - \cos \varphi)$$

Figure 5. Determination of the overturning of a single tree with hemisphere root–soil plate lump with failure radius $r_f$. We assume that the weight of the tree disperses with the angle of internal friction.
The stress acting on the overturning slip surface consists of two components. The first component is provided by the tree weight ($\sigma_t$):

$$\sigma_t = \frac{m_t g}{S_0}$$

(9)

where $m_t$ is the tree weight, and $g$ is the gravitational acceleration. The second part of the overburden stress arises from the weight of the lump of soil ($\sigma_l$). We consider the stress at the center of mass of the lump of soil as follows [53]:

$$\sigma_l = \frac{4r_f}{3\pi \rho_s g \cos \psi}$$

(10)

where $\psi$ is the slope angle, and $\rho_s$ is the soil density. Meanwhile, the presence of the root system on the slip surface adds an additional cohesive force to the soil [54], and the shear strength of the root-reinforced soil is calculated by the Mohr–Coulomb equation:

$$\tau = (\sigma_t + \sigma_s) \tan \phi + c + c_r$$

(11)

where $\tau$ is the shear strength, $c$ is the cohesion of the soil, and $c_r$ is the additional cohesion due to the presence of roots. The shear force generated when the soil–root plate moves were transformed into a root tension force, which could be divided into a tangential component and a normal component in the root system. Assuming that roots are elastic, initially oriented perpendicular to the slip plane, fully mobilized in tension and that $\phi$ is unaffected by root reinforcement, $c_r$ can be defined as follows:

$$c_r = \sum T_{ri} (\sin \delta + \cos \delta \tan \phi) RAR_i$$

(12)

where $\delta$ is the angle of deformed roots about the shear surface, $T_{ri}$ is the mean tensile strength of the roots, and $RAR_i$ is the root area ratio of $D_i$. The values are approximated to 1.2 [55] and so Equation (12) can be rewritten as follows:

$$c_r = \sum 1.2 T_{ri} RAR_i$$

(13)

Then the moment provided by the shear resistance of the soil can be expressed as follows:

$$M_s = \tau r_f S_0$$

(14)

Since coarse roots often show slip-out rather than breakage on the overturning slip surface [56], and the overturning slip surface is far from the trunk. The anchorage force is mainly provided by the coarsest tap root, the resistance of a tap root to lateral loads has been modeled based on the engineering theory of the resistance of piles to lateral loads. Assuming that the tap root rotates and bends towards its tip the maximum resistance to lateral loading can be expressed by the following equation [57,58]:

$$M_t = \frac{9}{2} \tau D' L^2$$

(15)

where $D'$ is the thickest root diameter on the overturning slip surface, and $L$ is the length of the root outside the overturning slip surface. Therefore, the total anti-overturning moment on the slip surface ($M_c$) can be expressed as follows:

$$M_c = M_s + M_t$$

(16)

3. Results

3.1. Root Biomass and Distribution

The overturning strength of different tree species is mainly affected by the root distribution characteristics [59]. To better understand the functions and roles played by roots...
of different diameters, roots above 10 mm were counted separately from those below 10 mm, and data from samples at different horizontal or vertical distances were counted (Figure 6). The biomass characteristics were fitted to the asymptotic Equation (2) to obtain cumulative root biomass curves and root attenuation coefficients ($\beta$) for plants of different DBH as shown in Figure 6. L. leucocephala roots develop mainly in a vertical direction, with thick, straight taproots, and numerous horizontal root systems developing on the vertical taproots, which are more numerous but relatively thin compared to the vertical roots.

![Graphs showing root biomass distribution](image)

Figure 6. Root biomass horizontal (a) distribution characteristic, (b) cumulative fraction and vertical (c) distribution characteristic, (d) cumulative fraction.

Figure 6 shows that the vertical taproot biomass accounted for almost 80%–90% of the total underground biomass, and almost 80%–90% of the roots were concentrated at a depth of 60 cm on the surface. The horizontal attenuation coefficient $\beta$ of the root system varied between 0.848 and 0.938, while the vertical attenuation coefficient $\beta$ varied between 0.965 and 0.973. Compared to the horizontal attenuation coefficient, the vertical attenuation coefficient was more stable than the horizontal attenuation coefficient, but it was still not a fit description of the effect of root distribution on overturning. Therefore, considering the shape of the root-soil plate of L. leucocephala, the radial distribution characteristics, and the cumulative curves of root biomass were obtained by counting the sample data in the radial direction towards the ball with the base of the plant as the origin (Figure 7). The radial characteristics compensated well for the differences caused by plant A3 growth specificity and corrected the errors caused by plant growth specificity to the model, while its root radial attenuation coefficient $\beta$ varied between 0.968 and 0.974, which was more stable than the horizontal and vertical attenuation coefficients and could better describe the root distribution characteristics of the plants during overturning.
The underground biomass of a sample of four plants was also counted, and the underground root biomass ($m_b$) of roots increased as DBH. Their relationship can be expressed by a function expressed as shown in Figure 8:

$$m_b = 11.11d_b^{2.53}$$  \hspace{1cm} (17)

The coefficient of determination $R^2$ was 0.99.

3.2. Root Tensile Strength

A total of 49 roots were successfully broken in tensile tests. The tensile strength ($T_r$) of roots decreased as the root diameter ($d_r$) increased; their relationship could be expressed by a power law function expressed as shown in Figure 9:

$$T_r = 46.44d_r^{-0.45}$$  \hspace{1cm} (18)
2.5311.11 = (17)

Figure 8. Relationship between DBH and underground root biomass.

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The coefficient of determination \( R^2 \) was 0.53.

3.3. Root Characteristics and Overturning Moment on the Overturning Slip Surface

The properties of the overturned trees were calculated and are listed in Table 3.

![Figure 9. Relationship between root diameters and underground root biomass.](image)

The \( L. \) leucocephala root system has developed a heart architecture, with the main biomass concentrated on the taproot. In the overturning experiments, it was observed that the root–soil plate had a hemispherical shape. Due to the high content of fine roots on the overturning slip surface, not all fine roots were broken, but there was an overall trend of coarse roots being pulled out and fine roots being broken. The distance of the thickest root
diameter was counted and found to be related to DBH, which can be expressed as shown in Figure 10:

\[ D = f(d_b, r) = (1.23814 - 0.01117r)d_b \]  \hspace{1cm} (19)

where \( r \) is the radial distance and the coefficient of determination \( R^2 \) was 0.89.

![Figure 10. Variation in thick root diameter with radial distance and DBH.](image)

The variation in the biomass and \( RAR \) of fine roots are shown in Figure 11. The variation in the biomass of fine roots with radial distance \( (r) \) was not significant, and the \( RAR \) was also changed inapparently with the different DBH, which was decreased by distance \( (r) \), and could be expressed by using a nonlinear regression approach as follows:

\[ RAR = 30.0219r^{1.3167} \]  \hspace{1cm} (20)

![Figure 11. Fine roots variation of (a) biomass and (b) \( RAR \) with radial distance.](image)

As the \( RAR \) for fine roots included all fine roots from 0 to 10 mm, and the roots of different diameters may contribute differently, the percentage of \( RAR \) for fine roots at different radial distances was counted (Figure 12), and the results were rather discrete, but showed a fluctuation of approximately 10%, and the contribution of 10% was considered for all fine roots of different diameters in this model.
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The root characteristics of 19 overturned trees on the overturning slip surface were also obtained, including the thickest root diameter ($D$), the root biomass, and the RD (Figure 13). The results showed that both the thickest root diameter and the root biomass at the overturning slip surface increased with the DBH, while the RD only showed a fluctuating trend at 1.29–6.58 kg/m$^3$, which may be a key factor in identifying the location of the overturning slip surface. Meanwhile, to verify the stability of the model, four sample trees at radial distances 20, 40, 60, 80, and 100 were brought into the model to calculate the thickest root diameter, root biomass, and RD (taking the biomass and the biomass per unit volume of the root within 10 cm radial distance of the radial overturning slip surface), the actual values were sampled and compared with the calculated values in the model, and the results are shown in Figure 13. The results suggested that the model could better predict the distribution characteristics of the coarse root diameter, root biomass, and RD.

Finally, the predicted and experienced values of the thickest root diameter, root biomass, and root density of A1 to A4 at radial distances of 20, 40, 60, 80, and 100 cm are shown in Figure 14a. Moreover, the DBH and root–soil plate radius of 19 overturning trees were brought into the model and the results obtained were compared with the experience values (Figure 14). The results suggested that the model can greatly describe the root distribution characteristics and predicted the critical moment of overturning with high DBH and generally overpredicted trees with low overturning strengths. Among them, the overestimated trees were B3, B6, B10, B15, B16, B17, and B19, which had DBH of 8–13 cm.
On the one hand, they did not form an obvious root–soil plate during the overturning process, which overestimated the shear strength provided by their soil. On the other hand, the small root–soil plate led to a relatively long anchorage length of thick roots, which also led to an overestimation of the anchorage force in the model.

![Figure 14](image-url)

**Figure 14.** Comparison of model-calculated values and experimental values (a) coarse root diameter and biomass and (b) tree critical overturning moment.

### 4. Discussion

Studies have considered the overturning slip surface outside the root range or assumed the location of the overturning slip surface by experience [35,53], which approach ignores the root characteristics that affect overturning. A model proposed here for tree overturning improved the description of the mechanical processes at the variation with root characteristics. This model incorporated plant growth characteristics on root characteristics on the overturning slip surface. The results suggested that the model could reflect the root distribution characteristics and the overturning moment, although overestimated the overturning moment of small DBH trees. It has been found that small DBH trees usually tend to experience stem breakage or bending before they reach their overturning moment in field surveys, but this had little effect on the model results.

#### 4.1. Role of Roots of Different Diameters in Overturning

To understand the relationship between tree resistance to overturning and root distribution characteristics. We investigated the effect of roots of different diameters in overturning. Fine roots were the most numerous in the root system and were able to regulate soil water. Meanwhile, the root system, which formed a complex fibrous network and assisted in imparting shear strength [60], was considered to play an important role in soil stability and was often used to calculate the additional cohesion provided by the root system [32,61]. The coarse roots, which were mostly taproots and sinker roots, penetrated deep into the ground and anchored trees in a solid layer, thus holding the shallow soil layer in place and maintaining the ability of the roots to maintain the soil–root complex as a whole [62,63].

Previous studies showed different views on the role of coarse roots and fine roots. Schwarz, et al. [64] used the root bundle model (RBM), and experiments showed that fine roots tended to slip out of the soil during tension or shear, while coarse roots tended to break up. In contrast, Ennos [56] reached the opposite conclusion in their experiments, observing that fine roots broke easily, while coarse roots slipped out of the soil. In this experiment, it was found that the fine roots on the overturning slip surface mostly showed breakage, and some of the coarse roots in the diameter range of 0.1–5.5 cm were pulled out. The taproot was pulled out for most trees except for a few accidental events, where taproot grew along the downhill direction and taproot twisted off or was interspersed in boulders of the debris flow deposition, and breakage occurred during the experiment.
Recent research shows that a large number of fine roots are more effective than a few coarse roots in anchoring the soil [65], but the important contribution of coarse roots still cannot be ignored [66], especially in the overturning process of trees, where fine roots and coarse roots differ due to the characteristics of the root system itself. Fine roots tend to form a root network that enables the soil to coalesce and its content influences the size and strength of the root–soil plate, while the coarse roots penetrate deep into the soil, forming the skeleton of the root–soil complex together with the boulders, and firmly anchoring the root–soil plate in the ground.

The role of coarse roots and fine roots was also reflected in the mechanical characteristics [64,67]. The maximum tensile force of roots of different diameters occurred at different root–soil plate displacements (Figure 15), meanwhile, trees of different DBH showed similar characteristics during overturning, and the soil–root plate displacement increased with DBH at the critical overturning moment. Considering the root distribution characteristics of the trees, the root–soil plate radius and the diameter of the coarse roots increased with DBH, while the fine root biomass changed inapparently at the overturning slip surface. As can be seen, the RD remained at a constant level at the overturning slip surface. It can be assumed that the overturning moment at different displacements may be caused by the mechanical properties of the coarse roots. Meanwhile, there were differences in the mechanical characteristics of roots and soils, with roots stretching 10%–20% of their length before being damaged under tension and soils stretching less than 2% [63]. The fine roots may be displaced together with the soil near the overturning slip surface before reaching maximum displacement, during which the coarse roots also begin to gradually assume the force component and failure at some extreme moment. This is the reason for the significant displacement of the root–soil plate before the overturning moment.

Figure 15. Mechanical behaviors of the trees overturned moment of different DBH at different root–soil plate displacements.

4.2. Influence of Root Distribution Characteristics on Tree Overturning Strength in the Debris Flow Accumulation Area

Plant growth is influenced by soil, moisture, and spatial location conditions, and plant root growth varies considerably between species, which also affects the position of the overturning slip surface [44]. Boulders of 10–20 cm in diameter were excavated occasionally during the sampling and deposited by debris flow; these boulders can easily influence the growth and spatial distribution of roots in the debris flow accumulation area, such as the growth direction of A3 taproots, which was shifted by a large boulder. Meanwhile, the root systems tended to be interspersed into the gaps of boulders, which held soil and boulders in place and thus enhanced the strength of the soil–root complex. Achim and Nicoll [68] investigated the radius of the root–soil plate of trees in different soil properties and found that the size of the root–soil plate was mainly affected by root distribution. These differences produced some slight fluctuations in the critical overturning moment,
which were not significant. The tree’s resistance to overturning was still determined by the position of the overturning slip surface under the influence of root distribution and root architecture [69]. Therefore, understanding the root characteristics of the overturning slip surface is helpful for the analysis of the overturning process.

In general, the root system firmly grips the soil, which creates a hard root–soil plate when the tree is overturning [29], and the process of overturning is reflected in the balance between the external forces and the resistance forces of the root–soil complex. In practice, however, overturning slip surface did not occur at the interface where the root system extended; rather, it occurred at the weaker interfaces within the root–soil complex. Ennos [56] suggested that failure will occur proximally before the fine distal roots are mechanically stressed in whole root systems. Coutts [63] also found through displacement curves of the root–soil plate that soil damage during overturning occurs first under the trunk and then spreads towards the edge of the plate, so that the overturning slip surface formation is then reflected in the balance between the ability of the root–soil complex to remain integral and the resistance of the weak slip surface, which can be characterized by the distribution of the root system.

As shown in Figure 13, both the thickest root diameter and the root biomass at the overturning slip surface increased with the DBH, while the RD showed only a fluctuating trend. Considering the roles of coarse roots and fine roots in the overturning process, the thickest root diameter and the root biomass can be used to measure the anchorage and shear strength provided by the root system, respectively, while the RD indicates the trend of shear strength on the overturning slip surface. As the radial distance from the tree increased, the RAR of the fine roots at this spatial location decreased, resulting in a decrease in the strength of the root–soil complex, the diameter of the coarse roots became thinner and the anchor length was shortened, resulting in a decrease in the anchoring moment provided by the coarse roots, furthermore, the radial distance gradually increased until the root–soil complex was unable to maintain its integrity, thus forming an overturning slip surface and causing the tree to overturn.

5. Conclusions

This study analyzed the effect of root distribution characteristics on the overturning resistance of trees and the location of the overturning slip surface. The model proposed here for tree overturning improves the description of root characteristics of the mechanical processes for tree overturning. This model is appropriate for trees with heart root architecture and distribution characteristics, such as L. Leucocephala. For trees with other root types of trees, more data are needed for verification.

1. Combined with field data, as the radial distance from the tree increased, the root cross-sectional area ratio (RAR) of the fine roots at this spatial location decreased, resulting in a decrease in the strength of the root–soil complex, the diameter of the coarse roots became thinner and the anchor length was shortened, resulting in a decrease in the anchoring moment provided by the coarse roots. The root–soil plate radius, the thickest root diameter, and the root biomass at the overturning slip surface increased with the diameter at breast height (DBH).

2. The content of roots affected the strength of the overturning slip surface, while the root density (RD) may be a key factor in identifying the location of the overturning slip surface. During the overturning process, the fine roots may be displaced together with the soil near the overturning slip surface before reaching maximum displacement, during which the coarse roots also begin to gradually assume the force component and failure at some extreme moment.

The model could describe the distribution characteristics, the overturning moment of trees, and the root characteristics on the overturning slip surface. Although it overestimated the overturning moment for trees with a small DBH, the results will be useful for understanding the influence of root distribution characteristics in overturning and the application of hazard resilience to forestry, which is affected by nature hazards.
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