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ROLE OF PLANT ROOT MORPHOLOGY IN THE STABILITY OF VEGETATED SLOPES

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ABSTRACT

This research aims to investigate the role of branching orientation of the root structure system in the stability of vegetated slopes. The effect of tap root anchoring in the firm layer on the stability of the slope is also investigated. Three-dimensional (3-D) finite element models associated with 3-D root architectures are established to analyze the stability of vegetated slopes. The branching pattern of the plant root system noticeably affects the stability of vegetated slopes. Tap roots contribute the most to the stability of slopes, followed by oblique roots at the downslope of the tree stem. The contribution of lateral roots at the downslope of the tree stem to the stability of slopes is less than that of oblique roots. The anchoring of tap roots in the firm layer considerably enhances the stability of the vegetated slopes and restrains the soil movement in the slope. Coarse oblique roots at the downslope side of the tree stem provide more contribution to the stability of the slope compared with that at the upslope side of the tree stem.

Key words: Root-soil interaction, root morphology, factor of safety, finite element model.

1. INTRODUCTION

Plant and its root system are important parts in the stability of slopes. The key issues for the assessment of the stability of vegetated slopes are: (1) the proper evaluation of the shear resistance contributed by the root system; and (2) the technique for modeling the stability of vegetated slopes. Root reinforcement in the soil has been extensively investigated, both experimentally (Docker and Hubble 2008; Fan and Chen 2010) and analytically (Waldron 1977; Pollen and Simon 2005; Schwarz *et al*. 2010) in the past few decades. Additionally, a number of methods have been proposed for analyzing the stability of vegetated slopes. Most of the proposed methods were based on a two-dimensional framework. A so-called "additional soil cohesion model" was proposed to represent the shear strength of the rooted soil zone by using additional cohesion to represent root reinforcement, and the model was associated with limit equilibrium analyses (Greenway 1987; Greenwood *et al*. 2004; Hubble *et al*. 2010) or finite element analyses (Kokutse *et al*. 2006; Ji *et al*. 2012). Nevertheless, the branching pattern of the root system structure cannot be properly modeled in the 2-D framework. The contribution of a plant root system to soil reinforcement is considerably affected by the root morphology of the plant (Fan and Chen 2010; Ghestem *et al*. 2014) and root traits (Baets *et al*. 2008; Stokes *et al*. 2009; Ghestem *et al*. 2014). This issue plays an important role in the stability of vegetated slopes. The reliability of assessing the stability of vegetated slopes in a 2-D model will remain unclear if the root system structure cannot be properly modeled.

Jewell and Wroth (1987) indicated that the contribution of reinforcements to the shear strength of the soil relies on the reinforcement orientation with respect to the shear direction, as the shear surface intersects with the reinforcement. Reinforcements may undergo compression if the reinforcement orientation away from the normal of the shear plane ranges from 90° to approximately 150°. Kokutse *et al.* (2006) analyzed the stability of vegetated slopes by using the three-dimensional finite element procedure. Different plant root systems, *i.e.,* the tap root system, heart root system and plate root system, were modeled by different geometries in the rooted soil zone. An additional cohesion was assigned to the rooted soil zone to represent the contribution of roots to the soil shear strength. Tap root systems are more efficient than plate and heart root systems in reinforcing slopes against landslides. Fan and Lai (2014) established a finite element (FE) model to investigate the influence of the spatial layout of planting on the stability of vegetated slopes. The plant root architecture was embedded in the soil to take into account soil-root interactions, and some of the roots penetrated into the firm layer. Vegetation at the higher and middle elevations of a slope provides better resistance to the stability of the slope with respect to that located at the downslope if the root system penetrates into the weathered rock bed. Ghestem *et al.* (2013) indicated that architectural traits above and below the shear plane play an important role in the contribution of shear resistance to the soil. Coarse roots perpendicular to the shear direction contribute the most to the shear resistance of the soil. Coarse roots behave more like anchors below the shear plane. Mao *et al.* (2014) performed direct shear tests on rooted soils using 3D FE analyses to investigate the influence of root orientations relative to the shear direction and of root traits on the shearing resistance. Parallel roots were implanted in the soil. Root geometry, root orientation relative to shear direction and mechanical traits considerably affect the contribution of root reinforcement to the soil.

The "additional soil cohesion model" has been frequently used in the stability analysis of vegetated slopes; however, the soil-root interaction cannot be properly taken into account. The role of

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the soil-root interaction in the stability of vegetated slopes remains unclear. In addition, the branching pattern of the root system governs the root orientation with respect to the driving force in the slope. Roots at different locations of the root system may have different contributions to the stability of the vegetated slope since root orientations play an important role in providing shear resistance to the surrounding soil. Nevertheless, research on this subject is limited to the scale of a slope.

This research aims to investigate the role of roots at various locations, and with different orientations in the root system, in the stability of vegetated slopes. Three-dimensional finite element models, along with proper modeling of the root system architecture in the soil, are established. The mechanical behavior of the soil-root interface is accounted for in the numerical model. The role of lateral roots and oblique roots at various locations in the root system in the stability of the slope is investigated, and the influence of tap root length and anchoring in the firm layer on the stability of the slope is also studied. In addition, the mechanical mechanism of the vegetated slope with root anchoring in the firm layer is analyzed and discussed.

2. MATERIALS AND METHODS

2.1 Numerical Models

Three-dimensional FE models were established to analyze the stability of vegetated slopes. The root system in the model is based on the investigation of a number of exposed plant root systems in a slope covered with mixed woods. Figure 1(a) shows the root systems of *Swietenia mahagoni* (L.) Jacq., with a falling tree in front of it, and the root diameter in the root system ranges from 8 to 13 cm. Figure 1(b) shows another plant root system exposed in a hillslope.

The vegetated slope in the numerical analysis consists of top soil underlain by a firm layer. The slope gradient is 45°, and the thickness of the top soil is 2.22 m. The length and width of the slope are 14 m and 21 m, respectively. The geometry of the vertical profile of the slope is shown in Fig. 2(a). The FE mesh of the 3-D vegetated slope established using the computer program PLAXIS 3-D is shown in Fig. 2(b). The 3-D finite element mesh of the vegetated slope consists of 109550 elements. Vegetation is arranged in three rows in the slope. The root systems at the upper, middle and lower parts of the slope are located at 7.5 m, 5 m and 2.5 m from the toe of the slope, respectively. The tree spacing is 2 m. The root structure is mainly placed within the top soil in the slope. The bottom boundary of the finite element mesh is fixed against displacement in the *x*-, *y*-, and *z*-directions. The vertical model boundaries with their normal in the *x*-direction are fixed in the *x*-direction and free in the *y*- and *z*-directions. The vertical model boundaries with their normal in the *y*-direction are fixed in the *y*-direction and free in the *x*- and *z*-directions. The ground surface is free in all directions.

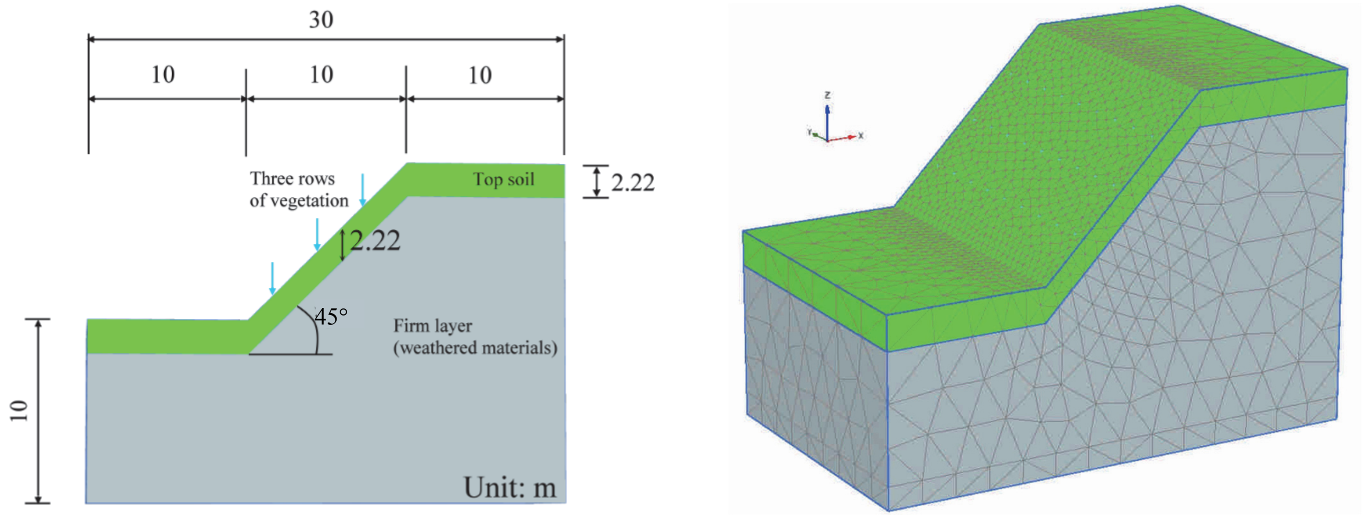
The root system architecture is incorporated in the numerical model, and the roots are modeled by using slender elements with circular cross-sections. The root diameter used in the model is based on investigation of the exposed root system of *Swietenia mahagoni* (L.) Jacq. (Fig. 1), and 0.1 m is used for the root diameter in the root system. The soil-root interaction and bonding resistance in the soil-root interface are taken into account in the analysis. Root elements are 3-node line elements with three translational degrees of freedom and three rotational degrees of freedom per node, and can sustain bending resistance and longitudinal deformation. Groundwater conditions are not taken into account in the analysis.

The branching pattern of the root structure used in the model is based on the investigation of exposed root systems in a hillslope. A number of features of the root system used in the numerical model are: (1) the root system consists primarily of tap roots, lateral roots and oblique roots; (2) the tap root grows vertically; (3) the number of roots in the downslope of the tree stem is more than that at the upslope side; and (4) the root length at the downslope of the tree stem is longer than that at the upslope side. Based on the features described above, the architecture of the root structure used in this study is established as: (1) three sets of lateral roots and oblique roots are arranged uniformly in the upslope side of the tree stem, four sets of lateral roots and oblique roots are arranged uniformly in the downslope side of the tree stem, and one set of lateral roots and oblique roots is placed at both sides of the tree stem with respect to the sloping direction; (2) the angles between each neighboring root at the upslope and at the downslope of the tree stem are 45° and 36°, respectively; (3) a single tap root is arranged in the root system with a length of 1.2 m; (4) the orientations of lateral roots and oblique roots with respect to the slope surface are 5° and 30°, respectively; (5) root lengths at the upslope and the downslope of the tree stem are 0.8 m and 1.2 m, respectively; and (6) the root diameter is 0.1 m to imitate coarse roots for trees in the forest. The diameter for each root in the root system is

(a) Root system of Swietenia mahogoni (L.) Jacq

(b) Unknown plant species

Fig. 1 The exposed root systems



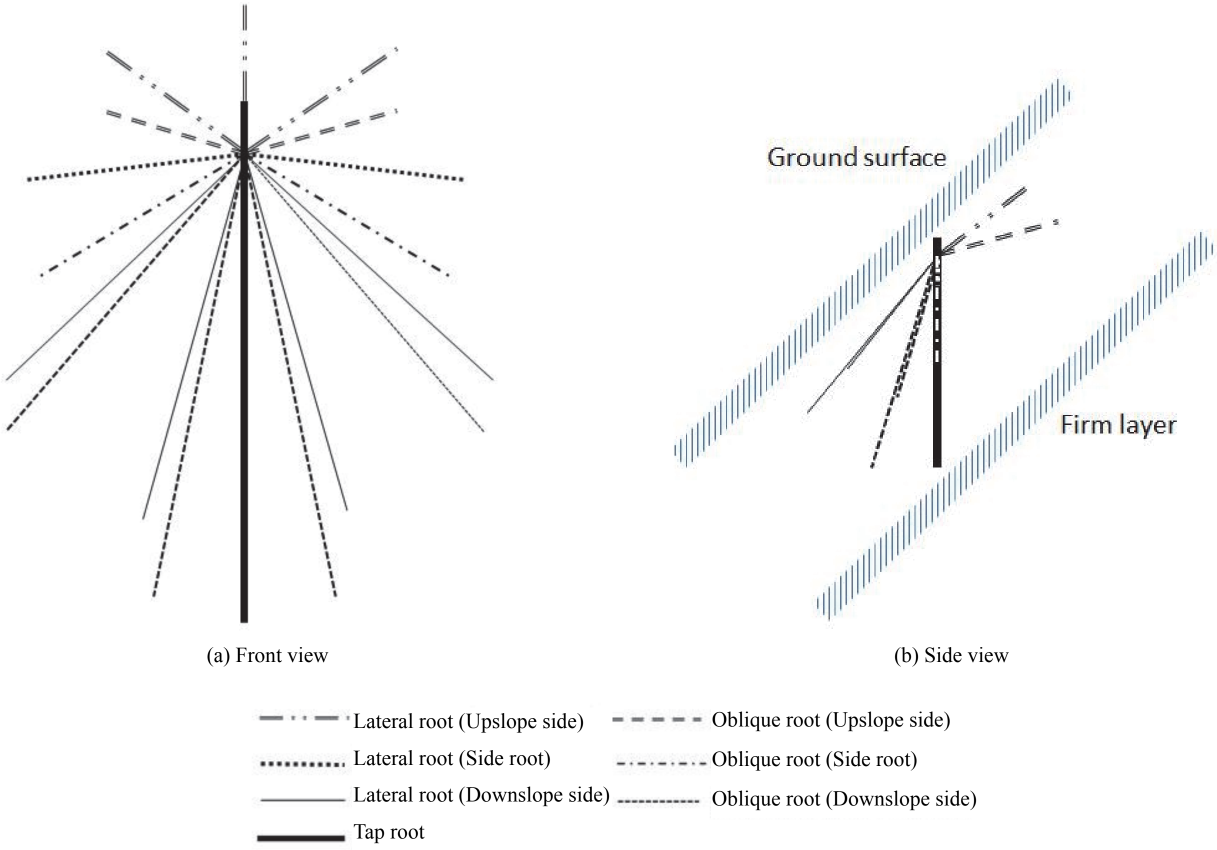
(a) Geometry of the vertical profile of the slope

(b) 3-D FE mesh

Fig. 2 Geometry and FE mesh of the vegetated slope

identical to minimize the influence of root geometry (diameter) on the role of roots at different locations in the stability of the slope. The standard root system architecture used in the FE modeling in this study is shown in Fig. 3. Additionally, different tap root lengths (0 m, 1 m, and 2.62 m) are also assigned in the model to investigate the influence of root anchoring in the firm layer on the stability of slopes.

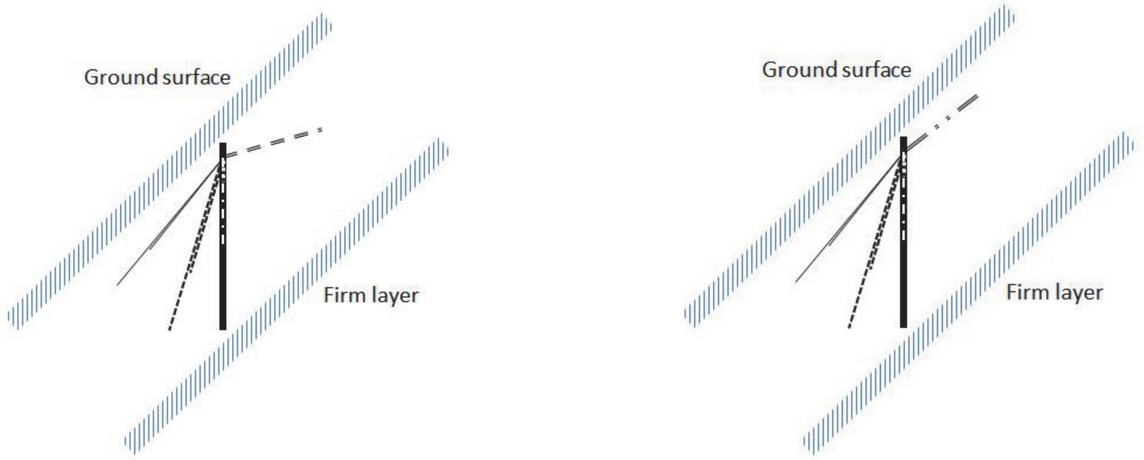
Roots at different locations in a root system with respect to the dip direction of the slope are deactivated in the FE model to investigate the role of roots with different orientations in the stability of the vegetated slope (Fig. 4). Vegetated slopes with the root system structures in Figs. 4(a) ~ 4(f) are used to investigate the role of lateral roots at the upslope, oblique roots at the upslope, lateral roots at the downslope, oblique roots at the downslope, lateral roots at the side and oblique roots at the side of the tree stem, respectively, in the stability of vegetated slopes.



(a) Front view

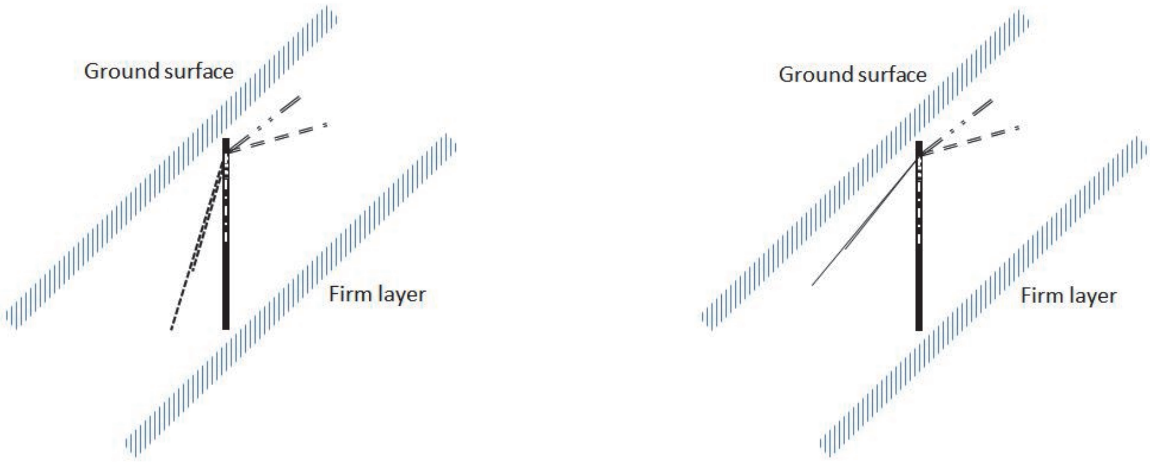
(b) Side view

Fig. 3 The branching pattern of the 3-D root system used in this study



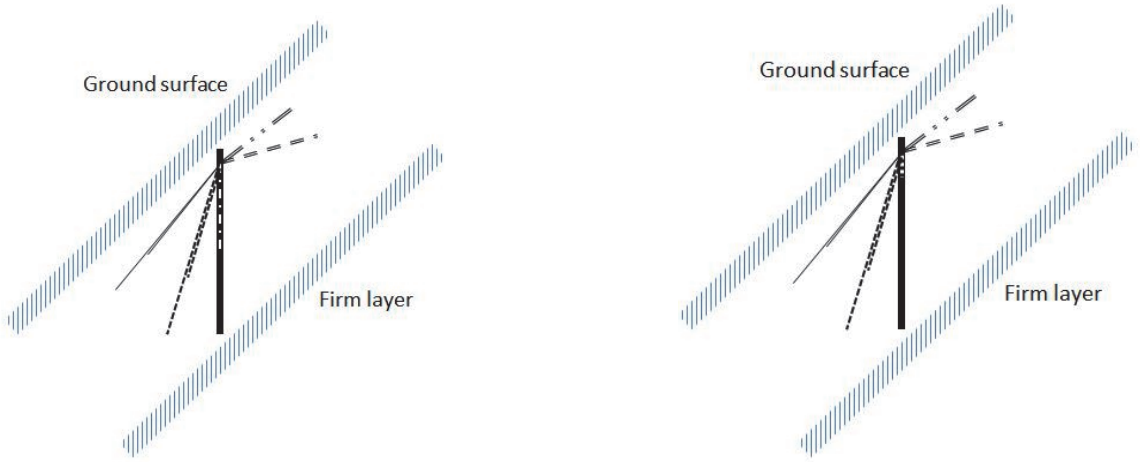
(a) Without lateral roots at the upslope of the tree stem

(b) Without oblique roots at the upslope of the tree stem



(c) Without lateral roots at the downslope of the tree stem

(d) Without oblique roots at the downslope of the tree stem



(e) Without lateral roots at the side of the tree stem

(f) Without oblique roots at the side of the tree stem

Remarks: The line types are described in Fig. 3

Fig. 4 Various types of root structures (side view)

2.2 Properties of Soils and Roots

The Mohr-Coulomb model is used to simulate the stress-strain behavior of the geological materials. The parameters used for the top soil and the firm layer in this study are illustrated in Table 1. The properties of the top soil are typical values for residual soils from sandstones embedded with shales in the hillslope. Roots are modeled using beam elements that can be placed in arbitrary directions in the soil. The bond strength between the soil and the beam is assigned in the analysis. The input parameters required for root elements are the elastic modulus, unit weight and soil-root bond strength. Fan and Lai (2014) summarized data of the elastic modulus of roots and the soil-root bond strength reported in published research (Stolzy and Barley 1968; Waldron 1977; Operstein and Frydman 2000). The elastic modulus for roots with a diameter of 0.1 m was 200 MPa in the FE analysis, and the soil-root bond strength is 20 kPa. In addition, the unit weight of the roots used in this study is 1.47 kN/m^3 based on the data reported by Comas *et al.* (2002). The root properties used in the numerical analysis are illustrated in Table 2.

To further investigate the influence of root geometry and root properties on the role of root orientations in the stability of vegetated slopes, the root diameters (D = 0.002 m, 0.005 m, 0.01 m, 0.05 m, and 0.1 m) and the root Young's modulus (E = 5 MPa, 50 MPa, and 200 MPa) are varied in the FE analyses.

2.3 Factor of Safety of Slopes

The contribution of a plant root system to the stability of vegetated slopes is evaluated in terms of factor of safety. The strength reduction method (SRM) is used in the FE procedure to calculate the factor of safety for vegetated slopes. The strength parameters tanϕ and c values of the soil are successively reduced until the soil body reaches failure. This procedure has been used extensively in calculating the factor of safety of slopes. To investigate the contributions of the different parts of roots in a root system to the stability of a slope, the factor of safety of vegetated slopes implemented with different types of root branching (Fig. 4) is calculated.

The role of roots at different parts of a root system in the slope stability is assessed in terms of degree of root efficiency (DRE), and it is defined in Eq. (1).

$$\mathrm{DRE} = \frac{\mathrm{FS}_s - \mathrm{FS}_d}{\mathrm{FS}_s - \mathrm{FS}_b} \times 100\% \qquad (1)$$

where FS$_s$ = factor of safety for the slope with the standard root structure in Fig. 3; FS$_d$ = factor of safety for the vegetated slope with the root structure free of the designated roots (Fig. 4); and FS$_b$ = factor of safety of the bare slope.

Table 1 Properties for the top soil and weathered rock (decomposed rock fragment)

	Top soil	Weathered rock (Decomposed rock fragment)
Unit weight (γ) (kN/m^3)	16	22
Young's modulus (E) (MPa)	6	500
Poisson's ratio (ν)	0.3	0.2
Cohesion (c) (kN/m^2)	10	100
Friction angle (ϕ) (°)	28	40

Table 2 Properties and geometry of roots used in the study

Unit weight (kN/m^3)	Root diameter (m)	Young's modulus (E) (MPa)	EI (kN·m^2)	EA (kN)	Soil-root bond strength (kPa)
1.47	0.1	200	0.98	1570	20

Remarks: To investigate the effect of root geometry and root properties on the stability of vegetated slopes, root diameters vary from 0.002 m to 0.1 m, and Young's moduli (E) of the root vary from 5 MPa to 200 MPa in the numerical analysis

In addition, the contribution of tap roots with different lengths to the stability of the vegetated slope is presented by means of the percentage of increase (PIF) in the factor of safety with reference to the FS value free of tap roots (Eq. (2)).

$$\mathrm{PIF} = (\mathrm{FS}_{dt} - \mathrm{FS}_{nt}) / \mathrm{FS}_{nt} \times 100\% \qquad (2)$$

where FS$_{dt}$ = factor of safety for the vegetated slope with different length of tap roots and FS$_{nt}$ = factor of safety of the vegetated slope free of tap roots.

3. RESULTS

3.1 Influence of Root Orientations on the Stability of Vegetated Slopes

The contributions of plant roots at different parts in a root system to the stability of the vegetated slope is evaluated in terms of factor of safety of slopes with designated roots deactivated in the FE analysis (Fig. 4). The factors of safety for the vegetated slope with three rows of standard root structures (Fig. 3) and for the bare slope are 1.508 and 1.405, respectively.

The factor of safety for the vegetated slope free of tap roots drops considerably compared to that with the standard root structure (Table 3). In addition, the factor of safety of the vegetated slope free of roots at the downslope side of the tree stem also noticeably lessens with respect to the slope with the standard root structure. The contribution of roots at different parts in a root system to the slope stability can be demonstrated by the equation defined in Eq. (1) (DRE values).

The higher the DRE value is, the more efficient the designated roots are. The DRE values for various root structure systems are shown in Fig. 5 and Table 4. The DRE value for the tap root is 73.78% (Table 4), and this value is considerably higher than those at other locations of the root system. In addition, the oblique roots around the tree stem show a greater contribution to the stability of

Table 3 Factor of safety of vegetated slopes with different types of root branching structures with respect to the standard type of root structure

Type of root structure Location	Root structure free of lateral roots	Root structure free of oblique roots	Root structure free of lateral and oblique roots	Root structure free of tap roots
At the upslope of the tree stem	1.498	1.497	1.5	–
Beside the tree stem with respect to the dip direction	1.501	1.5	1.5	–
At the downslope of the tree stem	1.499	1.480	1.478	–
At the center of the tree stem	–	–	–	1.432

Remarks: The factors of safety for the vegetated slope with the standard root structure and for the bare slope are 1.508 and 1.405, respectively. Root diameter used in this table is 0.1 m

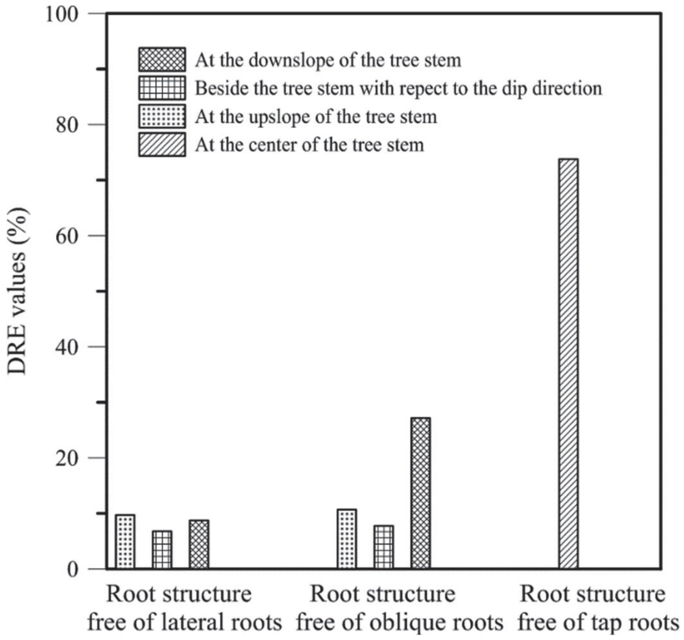


Fig. 5 Percentage (DRE values) of contribution of roots at different growth zones in a root system

Table 4 Percentage (DRE values) of contribution of roots at different parts in a root system to the slope stability

Type of root structure / Location	Root structure free of lateral roots	Root structure free of oblique roots	Root structure free of tap roots
At the upslope of the tree stem	9.71%	10.68%	
Beside the tree stem with respect to the dip direction	6.79%	7.76%	
At the downslope of the tree stem	8.74%	27.18%	
At the center of the tree stem			73.78%

Table 5 Influence of the length and anchoring of the tap root on the stability of vegetated slopes

	Free of tap roots	[1]Length of the tap root = 1 m	[1]Length of the tap root = 2.02 m	[2]Length of the tap root = 2.32 m	[3]Length of the tap root = 2.62 m
Factor of safety	1.432	1.442	1.508	1.539	1.578
Percentage of increase (PIF) in factor of safety with reference to that free of tap roots	–	0.69%	5.31%	7.47%	10.19%

[1]: The tap root is within the soil layer

[2]: The length of tap root anchoring in the firm layer 0.1 m

[3]: The length of tap root anchoring in the firm layer 0.4 m

the slope compared with the lateral roots, irrespective of the location in the root system. The DRE values are 27.18%, 10.68%, and 7.76%, respectively, for the oblique roots at the downslope, at the upslope and at the side of the tree stem. Thus, the oblique roots at the downslope of the tree stem are more efficient than those at the upslope and at the side of the tree stem. The DRE values are 8.74%, 9.71%, and 6.79%, respectively, for the lateral roots at the downslope, the upslope and at the side of the tree stem. The contribution of lateral roots at the upslope of the tree stem to the stability of the slope is slightly greater than that at the downslope and at the side of the tree stem.

3.2 Influence of Tap Root Anchoring on the Stability of Vegetated Slopes

The factors of safety for the vegetated slope without tap roots, with 1-m long tap roots, with 2.02-m long tap roots (without root anchoring), with 2.32-m long tap roots (root anchoring of 0.1 m in the firm layer) and with 2.62-m long tap roots (root anchoring of 0.4 m in the firm layer) are 1.432, 1.442, 1.508, 1.539, and 1.578, respectively (Table 5). The efficiency of tap roots (PIF values) with different lengths in the slope stability can be demonstrated by the equation defined in Eq. (2). PIF values vs. tap root lengths are shown in Fig. 6. The PIF values for the vegetated slope with tap root length of 1 m, 2.02 m (without root anchoring), 2.32 m (length of root anchoring = 0.1 m) and 2.62 m (length of root anchoring = 0.4 m) are 0.69%, 5.31%, 7.47%, and 10.19%, respectively (Table 5). The data show that root anchoring in the firm layer considerably enhances the stability of the vegetated slope. However, the strength properties of the firm layer may affect the bond strength of the root-soil interface, and in turn affect the level of contribution from root anchoring.

3.3 Effect of Root Diameter and Properties on the Stability of Vegetated Slopes

The influence of root diameter on the contribution of oblique roots at the upslope and at the downslope sides of the tree stem to the stability of the vegetated slope is shown in Fig. 7 in terms of

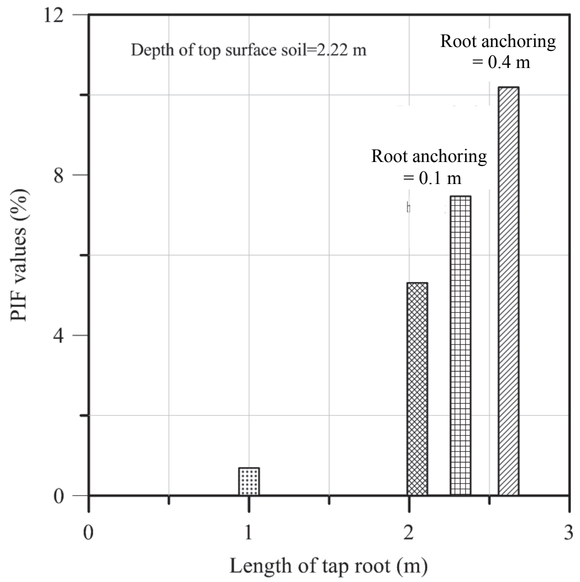
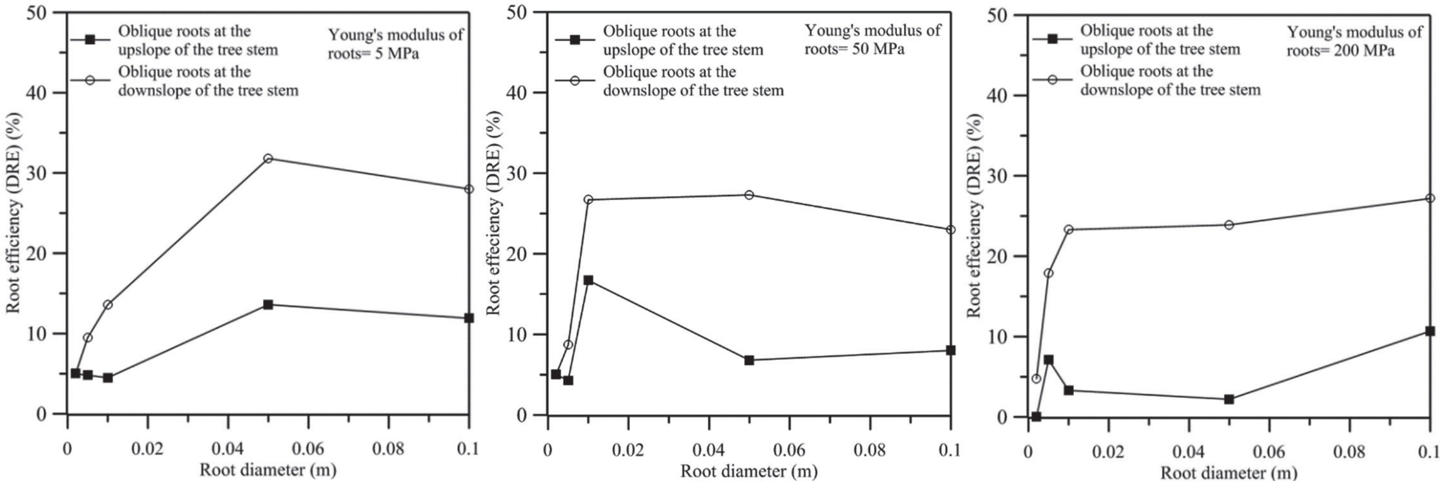


Fig. 6 Influence of the length and anchoring of the tap root on the stability of vegetated slopes



(a) Young's modulus of roots = 5 MPa (b) Young's modulus of roots = 50 MPa (c) Young's modulus of roots = 200 MPa

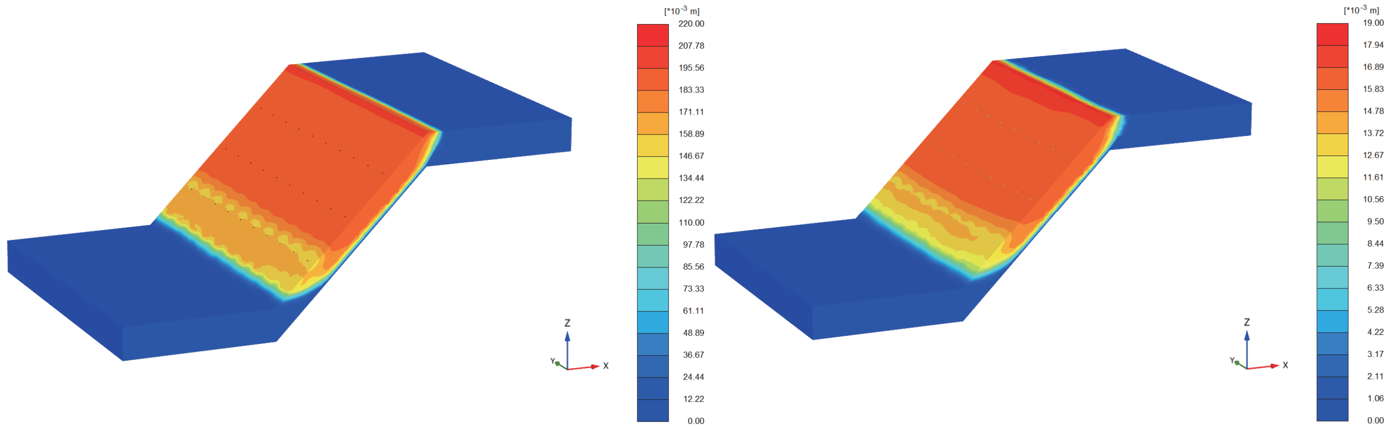
Fig. 7 **Influence of root diameter on the contribution of oblique roots at the upslope and at the downslope of the tree stem to the stability of the vegetated slope**

DRE values (Eq. (1)), as Young's moduli (E) of the root are 200 MPa, 50 MPa, and 5 MPa, respectively. These results showed that the oblique roots at the downslope side of the tree stem provide a greater contribution to the stability of the slope than that at the upslope side for a root diameter greater than 0.005 m, irrespective of the E values of the root. Roots with small diameters are considered to be highly flexible materials. For roots with low E values (= 50 MPa and 5 MPa in this study), however, the oblique roots at the upslope side of the tree stem show similar contribution to the stability of the slope with that at its downslope side at small root diameters ($D < 0.005$ m).

3.4 Effect of Tap Root Anchoring on the Mechanics of Vegetated Slopes

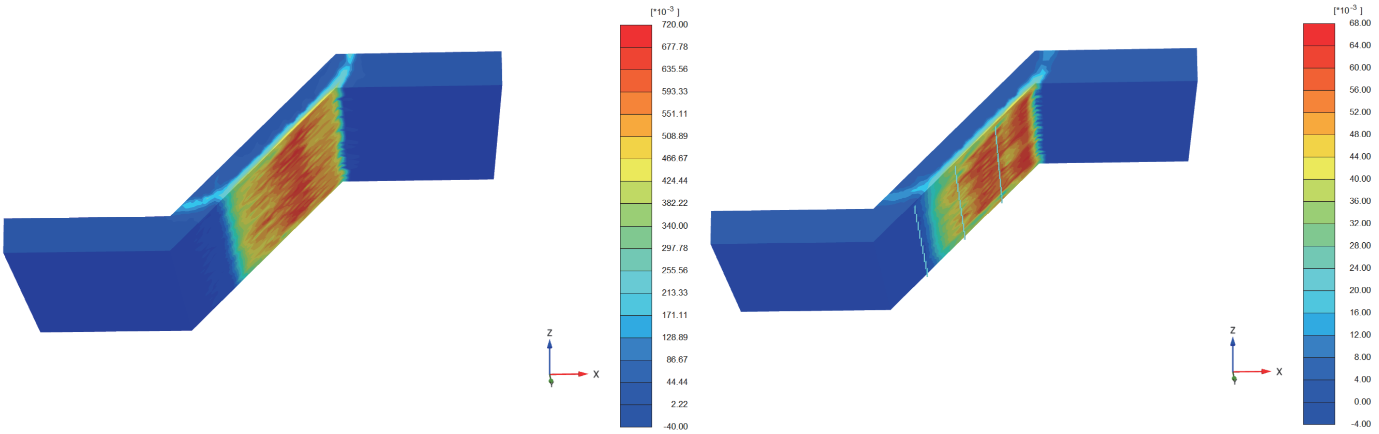
To investigate the role of tap roots in the mechanical mechanism of vegetated slopes, the numerical models without tap roots and with root anchoring in the firm layer were analyzed for vegetated slopes by conducting the SRM (Strength reduction method) analysis. Figures 8(a) and 8(b) show the distribution of total incremental displacement on the surface of the vegetated slope for the root structure without tap roots and with a 2.62-m long tap root (0.4-m root anchoring in the firm layer), respectively. For the vegetated slope with tap roots anchoring in the firm layer (Fig. 8(b)), soil displacements are restrained compared with that without tap roots, especially at the lower part of the slope.

In addition, Figs. 9(a) and 9(b) show the distributions of soil deviatoric strain on the side and the bottom of the top soil layer in the vegetated slope for the root structure without tap roots and with 2.62-m long tap roots (0.4-m root anchoring in the firm layer), respectively. Most of the deviatoric strains develop along the interface between the top soil and the firm layer. A shear zone (potentially sliding surface) is identified along the interface between the top soil and the firm layer. Root anchoring in the firm layer in the slope provides more resistance against development of deviatoric strain along the soil-firm layer interface, especially at the lower part of the slope. The results obtained herein further enhance the importance of root anchoring in the stability of vegetated slopes.



(a) without tap roots (b) 0.4-m-long tap root anchoring in the firm layer

Fig. 8 **The distribution of total incremental displacement in the top soil layer of the vegetated slope (by SRM analysis)**



(a) without tap roots

(b) 0.4-m-long tap roots anchoring in the firm layer

Fig. 9 The distribution of deviatoric strain in the top soil layer of the vegetated slope (by SRM analysis)

4. DISCUSSION

The results presented herein show that root orientations in the root system with respect to the sloping direction in a slope play an important role in the stability of vegetated slopes. Past research (Jewell and Wroth 1987; Wu *et al.* 1988; Mao *et al.* 2014) indicated that root stresses depended on root orientation with reference to the shear direction. The shearing resistance of rooted soils varies with the pattern of root orientations in a plant root system.

The research conducted herein showed that roots oriented perpendicular to the shear direction provided more effective shear resistance to the soil than that at other orientations. Roots at the downslope side of the tree stem (oriented away from the sliding direction in a slope) provide a greater contribution to the stability of the slope compared with that at the upslope side. Lateral roots oriented in the sliding direction in a slope (upslope side of the tree stem) contributed the lowest root reinforcement to the stability of the slope, especially the cable type of roots with low rigidity (low EI values). The sliding zone in the slope plays a role in the contribution of plant roots at different parts to the stability of the slope. Figure 9 shows the potential sliding zone for the vegetated slope in this study. The lateral roots in the root system implanted in the slope show slight relationship with the sliding zone, and the contribution of lateral roots to the stability of the slope is low. The oblique roots at the downslope side of the tree stem function as small micro piles in the slope, and its contribution to the stability of the slope is higher than that at the upslope side. The tap root interacts directly with the potential sliding zone. Thus, the factor of safety of the vegetated slope is downgraded significantly if the root system is free of tap roots.

Mao *et al.* (2014) indicated that the roots above the shear plane oriented in the same direction to the shear direction developed tension and showed a greater increase in the soil shear strength compared with that oriented in the opposite direction by performing numerical analyses on rooted soil mass subjected to shear. These results were somewhat different from the results conducted in this study. The numerical model conducted by Mao *et al.* (2014) demonstrated that the shear zone passes through the roots in the rooted soil mass. The deformation of the root was closely related to the location of the shear zone, and the root force may be noticeably mobilized if roots were subjected to shear in the rooted soil mass. In the scale of vegetated slope, the potential sliding zone (shear zone) runs through the area of top soil-firm ground interface, which is below the root system. The sliding zone in the vegetated slope may not directly interact with the root system, shown in Fig. 9. The shear deformation of the root system in the vegetated slope is considered to be not noticeable. The interaction of the location of the potential sliding (shear) zone with the root system in the slope plays an important role in the mobilization of root force and contribution of root reinforcement to the stability of the slope.

The role of roots at the downslope and at the upslope side of the tree stem in the contribution of slope stability is affected by the pattern of root system and root property. Roots at the downslope side of the tree stem are more effective than that at the upslope side for coarse roots with moderate to high Young's moduli (E values > 50 MPa in this study), whereas roots at the upslope and at the downslope side of the tree stem show similar contribution to the stability of the slope if roots have low flexural rigidity, *e.g.,* thin roots. Tensile forces may develop for plant roots with the highly flexible trait in a slope, whereas coarse roots may likely mobilize compressive forces and bending resistance in root systems, which was identified in the research by Schwarz *et al.* (2015). Root orientation, root geometry and Young's modulus play important role in the stability of vegetated slopes.

5. CONCLUSIONS

This paper investigated the role of roots with various orientations in a root system structure in the stability of vegetated slopes. Three-dimensional FE analyses on vegetated slopes implanted with plant root structures were carried out in the study. The 3-D geometry of the root structure and the properties of root elements were properly taken into account in the analysis. Coarse roots with a diameter of 0.1 m were used in the study, and the effect of root property and root diameter on the role of roots in the stability of the slope was investigated. Major findings summarized from this research are as follows:

1. Tap roots with a considerable length are considered the most effective root elements in stabilizing the slope compared with roots at other orientations in a root system.
2. Oblique roots at the downslope of the tree stem are more efficient in the stability of vegetated slope than that at the side and at the upslope of the tree stem for coarse roots. Oblique roots at the side of the tree stem provide similar resistance to

the stability of the vegetated slope to that at the upslope of the tree stem. In addition, the contribution of lateral roots at the upslope of the tree stem to the stability of the slope is slightly greater than that at the downslope and at the side of the tree stem.

3. Root anchoring in the firm layer can considerably enhance the stability of vegetated slopes compared to those without anchoring. The bond strength of the root-soil interface may affect the level of resistance from root anchoring.
4. The role of roots at the downslope and at the upslope side of the tree stem in the contribution of slope stability is affected by root diameter and property of the root. Oblique roots with low flexural rigidity at the upslope and downslope side of the tree stem provide similar contribution to the stability of the slope, whereas oblique coarse roots at the downslope side of the tree stem contribute are more effective in contributing to the stability of the slope than that at the upslope side.
5. The location of the potential sliding (shear) zone in the vegetated slope and its interaction with the plant root system play an important role in the mobilization of root force and in the stability of the slope.

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