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ORIGINAL PAPER

Effects of the Root's Distribution on the Stability of Slope

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Abstract Vegetation has been recognized to play a major role in the reinforcement of slopes against shallow landslides. The intensity of root reinforcement mainly depends on roots distribution and root tensile strength. The aim of this study is to determine the effects of morphological characteristics of vetiver roots system on slope stability. A series of experiments were carried out to obtain the physical and mechanical parameters of soil with vetiver roots. A preliminary analysis is performed to assess the impact of root morphologies on the slope's safety factor. The results indicate that the roots have significant influence on the shear strength parameters of slope soil. The increasement of cohesive force is more obvious than that of the intrinsic friction angle. Hence, combined the experiments and theory, the formula is deduced to calculate the safety factor of the slope considering the distribution angle of root system. Furthermore, when the angle between root system and shear surface reaches 156°, the root system works relatively better in reinforcement. It demonstrates that root orientations significantly affect the shear resistance provided by root-permeated soil. Finally, the implementation of soil-root reinforcement models was allowed to calculate the safety factors of shallow slope and evaluate the vegetation contribution to soil stability.

Keywords Vetiver root system · Slope stability · Safety factor · Cohesive force · Internal friction angle

1 Introduction

In recent decades, with the effects of engineering construction activities and the consequences of climate change, the severe degradation of mountainous and hilly regions due to soil erosions and landslides is a result. To deal with the problem, the subsequent measures have been practiced, such as nailing, retaining wall, geosynthetic reinforcement, and so on. Among these, engineering methods are not environmentally friendly for a reason that they are followed by a serious ecological environment (Bouazza et al. 2013; Huan et al. 2004). Therefore, vegetation is found to be a preferred remedial measure from economical, sustainability and environment points of view. The role of root system in improving slope stability has long been recognized (Mao et al. 2012; Son et al. 2019). Plant roots can increase soil shear strength both directly by mechanical reinforcing and indirectly through water removal by transpiration (Maffra et al. 2019; Ng and Leung 2012). Therefore, according to a geo-mechanical effect and a soil-hydrological effect, vegetation has generally a positive impact on the stability of soils on sloping

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(Chirico et al. 2013). The ability of plant roots to control mass wasting and soil slippage is said to originate in the ability of its deep roots to penetrate and hold the soil together (Abdi et al. 2010; Capilleri et al. 2019; Cislaghi et al. 2017). Many scholars also have made a lot of achievements in the effects of plant roots on slope reinforcement and soil erosion resistance. Yu et al. (2012) took the self-built test area around the Xining Basin as an example, they found that the plant root system in the test area has a significant reinforcement effect on the slope soil through the triaxial test on the root-soil composite samples in the cold and arid environment. Xiao et al. (2014) conducted a series of straight shear tests on the root-soil composite composed of two different plant root systems and investigated the influence of the plant root systems on the shear strength of the composite under different water contents and different root ratios. The results showed that the root systems of both plants could improve the shear strength of the root-soil composite, but their contributions to the shear strength index of the composite were different. Vetiver is known as the herb with the longest root system in the world and is a pioneering species for soil consolidation and slope protection (Truong et al. 2008). Vetiver planted in slopes can increase the shear strength of slope soils by up to 28.92 KN/m^2 per cent due to the interaction between the root system and the soil (Nilaweera and Hengchaovanich 1996). Aziz and Islam (2022) applied vetiver to different kinds of slopes and studied the role of vetiver grass on the stability of slopes through physical and numerical modeling, the results showed that the higher the vetiver cover, the higher the safety factor of the slope. They also found that under the same geometry of natural slope conditions, planting vetiver grass is more likely to reduce the possibility of shallow slope failure on sandy silt. These studies revealed the mechanism of soil strength reinforcement by roots and promoted the development of plant slope protection technology. A satisfactory way of quantifying and incorporating the biological effects into the slope stability analyses depends on the morphological characteristics of root system. Suitable roots distribution in slope is of great significance to protect slope stability.

This study will further develop the estimation of root reinforcement based on a series of laboratory shear tests of vetiver roots in slope soil at different angles with the potential slip surface. The model will be proposed to evaluate the quantifying root reinforcement for slope stability calculations.

2 Theoretical Analyses

Soil with sloping surfaces may be the result of natural agencies, or man-made. The slip surface of slope in homogeneous cohesive soil is in general a continued curve, assumed as circular arc. Roots are regarded as fibers distributed in the slope soil. Shear stress, transferred in the ground into a tensile resistance in the roots, carries out the mechanical soil reinforcement by the roots. Roots will increase the soil shear strength by tensile strength of its own roots and provide slope-shearing resistance. In this paper, stability calculations of vegetated slope over circular rupture surfaces would be conveniently performed by the method of slices. The cross-section of the slope-forming mass of soil encompassed by the circular rupture surface is subdivided into a number of vertical, parallel elements or slices. The forces acting on the slices are shown in Fig. 1. The frictions between neighbouring two slices are ignored.

In Fig. 1, MN line is used as the vertical line for plant roots. On the right side of MN line, roots are distributed to the uphill, while on the left side of MN line roots are distributed to the downhill. When the shallow slope soil mass slides downward, the roots toward the uphill direction will be subject to the tensile force due to the downward sliding of the soil. While the roots toward downhill subjected to compress will not be able to transfer the tensile strength into shear resistance. Consequently, all roots' tensile strength can't be mobilized. The effect of roots on soil reinforcement in the uphill area of the slope is only considered. It is supposed that the tensile force generated by the root j_{th} in slice i_{th} of soil mass is T_{ij}. The tangential component $F_{ij}^{'}$ of T_{ij} can be expressed as following:

$$F'_{ij} = T_{ij}\cos(a_i + \beta_{ij}) + T_{ij}\sin(a_i + \beta_{ij})\tan\varphi \tag{1}$$

where α_i is the angle (°) between the slide surface of the slice i_{th} and the horizontal plane. β_{ij} is the angle (°) between the root j_{th} and the horizontal plane in the slice i_{th} sliding soil mass. When the root is above the horizontal plane, β_{ij} is negative and it is positive when the root is below the horizontal plane. φ is the

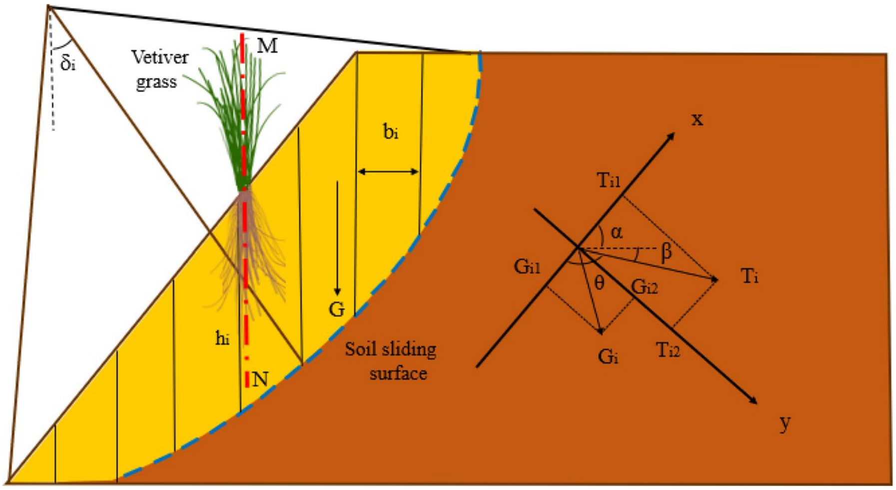


Fig. 1 Stability analysis of vegetated slope by the method of slices

intrinsic friction angle (°) of sliding soil. Formula (1) can be simplified as follows:

$$F'_{ij} = T_{ij}\left[\cos\varphi\cos(a_i+\beta_{ij}) + T_{ij}\sin(a_i+\beta_{ij})\sin\varphi\right]\frac{1}{\cos\varphi}$$
$$= T_{ij}\cos[\varphi-(a_i+\beta_{ij})]\frac{1}{\cos\varphi} \tag{2}$$

Literature showed the root tensile strength far exceeds the soil-root friction. Therefore, the tensile resistance is taken as the maximum resistance that the root system can bear. The root implantation has a greater influence on the cohesive force of the soil, but less on the intrinsic friction angle (Ali and Osman 2008). It is assumed that the increased anti-sliding force of the root system against the sliding of the soil is only regarded as increasing the cohesion of the soil. Then, the total resistance force generated by roots in sliding soil mass may be written as

$$\Delta c = \sum\nolimits_{i=1}^{n}\sum\nolimits_{j=1}^{m} T_{ij}\cos[\varphi-(a_i+\beta_{ij})]\frac{1}{\cos\varphi} \tag{3}$$

The weight G_i of slices can be resolved into a normal component $G_{i2}=G_i\cdot cos\delta_i$ and a tangential component $G_{i1}=G_i\cdot sin\delta_i$. The tangential components of the weights cause the mass to slide downward. The sum of all the tangential components may be expressed as $G_1=\sum G_{i1}$. The resisting force F_i acting on the base of any slice of length l_i is:

$$F_i = cl_i + \sigma\tan\varphi = cl_i + G_i\cos\delta_i\tan\varphi \tag{4}$$

where c is the cohesion of sliding soil mass (kPa). φ is the intrinsic friction angle of sliding soil (°). δ_i is the angle between the center of the circle and the center of the bottom of the i_{th} soil body and the vertical (°).

Finally, the safety factor of vegetated slope K can be written as follows:

$$K = \frac{\sum_i^n F_i + \Delta c}{\sum_i^n G_i\cdot\sin\delta_i}$$
$$= \frac{\sum_{i=1}^n cl_i + G_i\cos\delta_i\tan\varphi + \sum_{i=1}^n\sum_{j=1}^m T_{ij}\cos[\varphi-(a_i+\beta_{ij})]\frac{1}{\cos\varphi}}{\sum_i^n G_i\cdot\sin\delta_i} \tag{5}$$

To a given slope, if slid surface is assumed, many parameters will be constant, such as intrinsic friction angle, cohesive force, weight, sliding angle inclination, and sliding surface length. From the formula (5), we can find the safety factor K has a positive correlation with Δc whose value is dependent on α_i and β_{ij}. Presumed that the tensile force of root keeps constant. If

$$\varphi-(a_i+\beta_{ij}) = 0 \tag{6}$$

Then Δc will reach the maximum value. As showed in Fig. 1, we can find:

$$a_i+\beta_{ij} = 180^\circ-\theta_{ij} \tag{7}$$

where θ_{ij} is the angle (°) between the tangential direction of the bottom center of the i_{th} soil mass and root j_{th}. Taking the formula (7) into the formula (6), we can get

$$\varphi - (180^\circ - \theta_{ij}) = 0 \quad (8)$$

Then, the formula (9) can be obtained as

$$\theta_{ij} = 180^\circ - \varphi \quad (9)$$

That's to say, when θ_{ij} equals 180°-φ, the maximum Δc will make the K value biggest.

3 Materials and Methods

3.1 Soil Characteristics

Soil in this research was cohesive red soil, of which some soil properties (density, optimum moisture, liquid limit, plastic limit, cohesion and friction angle) were based on the results of laboratory tests. The stress–strain behavior of soil was here modeled using a Mohr–Coulomb model, in which the non-associated flow rule was used. The parameters for top soil are following as in Table 1.

3.2 Vegetation Characteristics

Besides soil erosion, the vetiver system can reduce or even eliminate many types of natural disasters, including landslides, mudslides and so on due to its long, massive, and complex root system (Du 2017; Mickovski et al. 2005). Root sampling of one-year vetiver took place in a man-made slope, located south of Changsha city in China. The roots distribution were recorded for these vetiver by excavating four individuals. Most roots diameters ranged from 1 to 2mm. Some roots less than 1mm were mainly distributed in soil 0–20 cm deep from surface (Fig. 2). It is found that the diameter of individual vetiver root matrix extends 20–25 cm and the number of roots declines with depth. However, the roots diameters were found less changed along the length of the root. As highlighted before, root tensile strength testing is a crucial step to evaluate root reinforcement. After excavation, the roots were stored in a plastic bag to preserve their moisture content. Root tensile strength tests were conducted in the laboratory with a tensile test machine (Fig. 3).

Table 1 Properties of soil

ρ/(g cm^{-3})	Optimum moisture/%	I_L/%	I_P/%	c/kPa	φ/°
1.68	21.5	41.5	25.4	12.17	23.68

Fig. 2 Root of vetiver

Tests results showed that the finer the roots, the higher their tensile strength. Hence mean tensile strength values obtained as Tr = 28MPa will be used to predict root reinforcement and an average Young's modulus of elasticity of E = 120MPa.

3.3 Laboratory Triaxial Shear Tests

In order to study the contribution of roots to soil, a series of triaxial shear tests have been performed on reconstituted unreinforced and vetiver rooted soil

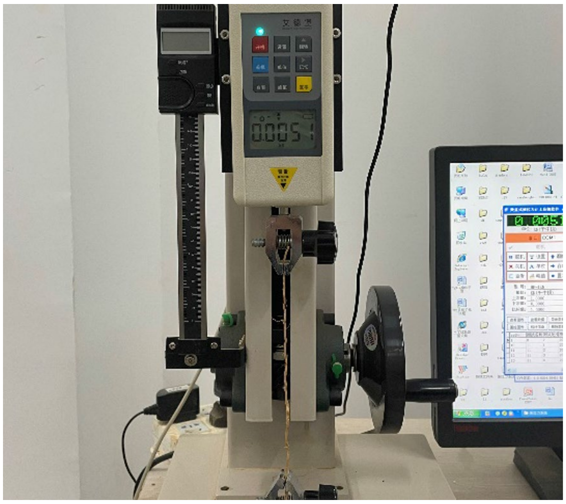


Fig. 3 The tensile machine

samples with the same density and moisture content to determine the shearing behavior of root-permeated soil. To observe the increase in shear strength from the vetiver-root reinforcement, bare soil with the same density and water content specimens were prepared for the triaxial shear tests as well.

Using a computer-controlled GSD equipped with a 50kN maximum axial load, triaxial tests were conducted to determine the value of shearing strength of root-soil composites (Fig. 4), whose results would be used to calibrate the numerical model.

The soil prepared with moisture of 21.5% was filled into the box and compacted in three layers up to a height of 80mm.The angle of shear distortion varied between 40° and 50° from the results of shear tests conducted by Waldron on various rooted-soil. Therefore, the angle of shear distortion is assumed to be equal to 45°.Vetiver roots are designed to be inserted into soil samples with different angles θ_j with shear plan to obtain the root-permeated specimens (Fig. 5). The triaxial tests were carried out on fresh roots within 3 days from sampling.

From the formula (9), we know that if θ_j is set as $180° - \varphi$, the safety of factor K would be maximum. Here the intrinsic friction angle φ of slop soil was obtained as 24° in the triaxial tests. So θ_j was about 156°. Other angles of roots with distortion shear plane were designed as 90°, 135°, and 180° to contrast. Eventually, same numbers of roots with diameter of 2mm and length of 15mm were cut and inserted into soil to get four groups of the root-permeated specimens arranged as $\theta_1 = 90°$, $\theta_2 = 135°$, $\theta_3 = 156°$, $\theta_4 = 180°$ respectively, including three samples in every group. There were four groups of rooted specimens and a group of non-rooted specimens carried out in the laboratory. In each group, three samples were sheared at a speed of 0.4mm/min under confining pressures of 50kPa, 100kPa and 150kPa respectively.

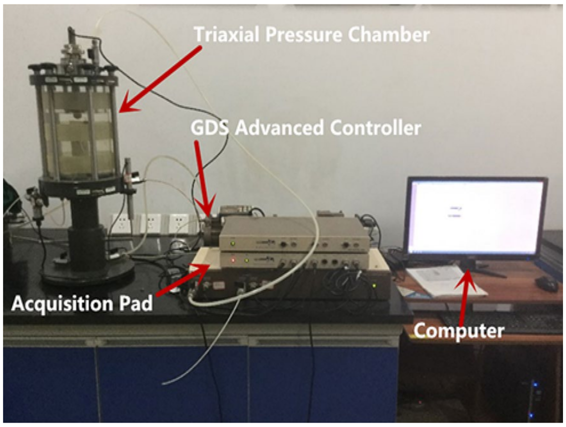


Fig. 4 Triaxial test

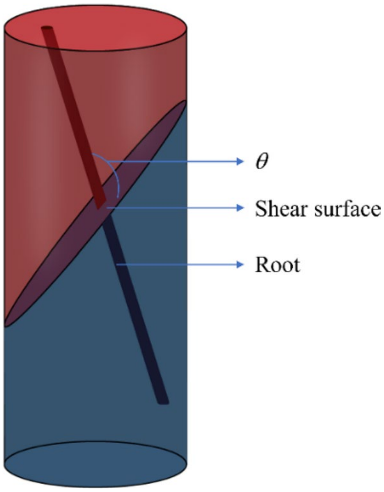


Fig. 5 Root-permeated specimens

3.4 Numerical Modeling

Finite element analysis was performed using SIMULIA software as a sub-program of the complete analysis procedure. The numerical simulation aimed at predicting the stability of vegetated slope despite some model simplifications basing on the results of triaxial shear tests in laboratory. A 2D plane strain Finite Element model with a height of 8 m was designed in order to analyze the mechanical stability of the studied slopes and investigate the effects of vetiver root system on the stability of a slope, as shown in Fig. 1. The model slope angle was set to 45°, it was partitioned at a depth of 1m from the slope surface, without considering the influence of groundwater (Fig. 6). The horizontal and vertical boundaries of the model were restrained. The bottom was subjected to horizontal and vertical constraints while surface and the top of the slope was unbounded.

Soil is strong in compression and weak in tension. Roots, one of the important mechanical characteristics of them is that they are strong in tension, assumed a role like steel (Świtała et al. 2018). A combined effect

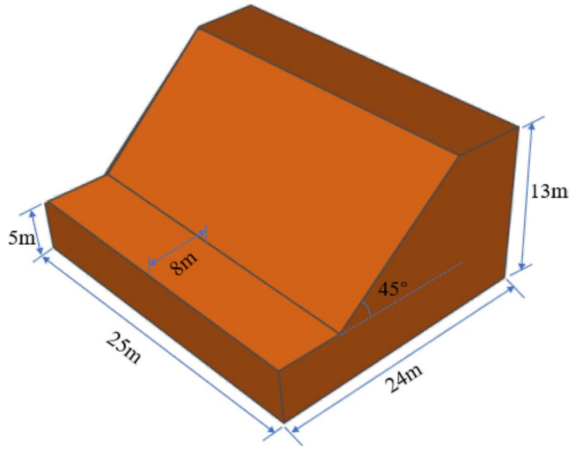


Fig. 6 Schema of the slope

of soil and roots results in a reinforced soil. When roots play a reinforcing role, they are subject to tension but not compression. Therefore, it is assumed the roots have no flexural stiffness. It is presumed that the soil is an ideal elastoplastic mass and complies with the Mohr–Coulomb yield criterion. The root-soil interaction was regarded as the mode of fiber reinforced soil and the root-soil complex was formed in the root zone. The geometrical model was partitioned at a depth of 0.5 m from the slope surface. The strip slope soil was consisted of the surface root-soil zone and the deep soil zone without roots. When the slope soil was discretized, CPE4 element was adopted for the soil. Further compaction was carried out if there was a root soil complex grid on the slope surface. Slop stability analysis was conducted on a hypothetical slope with and without roots using the strength reduction method in a two-dimensional finite element model.

4 Results and Discussion

4.1 Mechanical Characteristics of Root-Reinforced Soil

The shear strength of the soil-root composite is influenced by the mechanical reinforcement of vetiver roots. For this purpose, a series of laboratory triaxial shear tests reinforced soil with different angles roots were carried out in different cell pressures conditions. Then their stress deviation (σ_1–σ_3)-axial strain (ε) curves were plotted in Fig. 7.

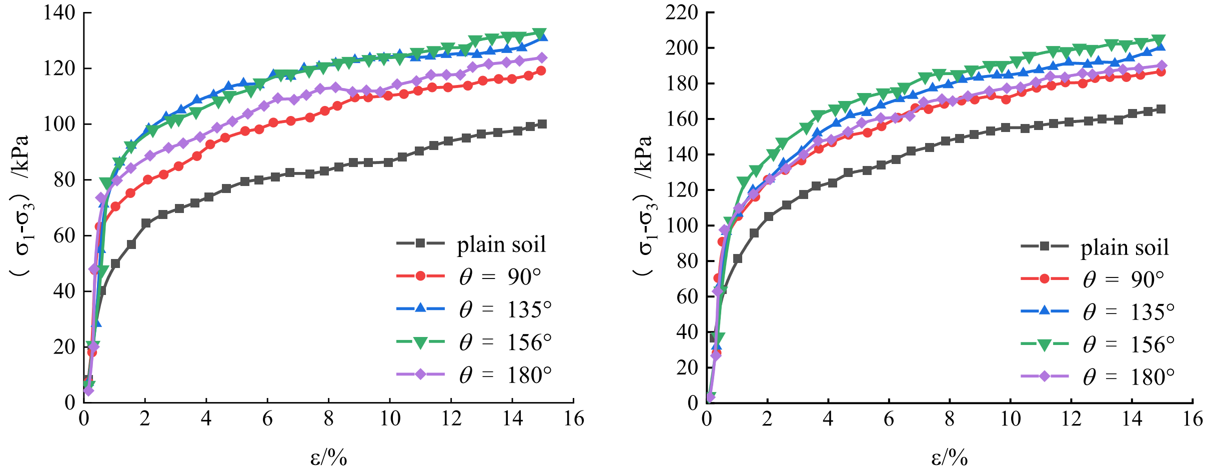
Figure 7 concerns the stress–strain curves of soil samples of different roots angle with shear surface. It is observed that the increment of about 9%, 17%, 20%,13% in stress deviation correspondingly in the reinforced soil with roots angles of 90°, 135°, 156°, 180° respectively. Compared to plain soil. Mohr circles of stress for each group of laboratory triaxial shear tests at critical states were obtained. By fitting the common tangent of the Mohr circles, the shear strength failure envelope of each group of soil samples can be gotten. Then the cohesion force and the intrinsic friction angle of soil samples with different inclination of root (θ) are obtained as Table. 2. From the theoretical equation of Coulomb shear strength and the increased values of shear strength parameters in Table 2, the increment of soil samples shear strength induced by roots at different inclination (θ) can be calculated, as shown in Fig. 8.

It can be seen from the Table 2 that shear strengths of soil with all different angles root have been improved. Compared with friction angle, cohesion force of rooted-soil was significantly increased. From Fig. 8, it was observed the increment of shear strengths of soil reaches to maximum when the angle between root and the potential slip surface of slope is 156°. The results of a series of laboratory triaxial shear tests have confirmed the contribution of roots to increment of soil shear strength.

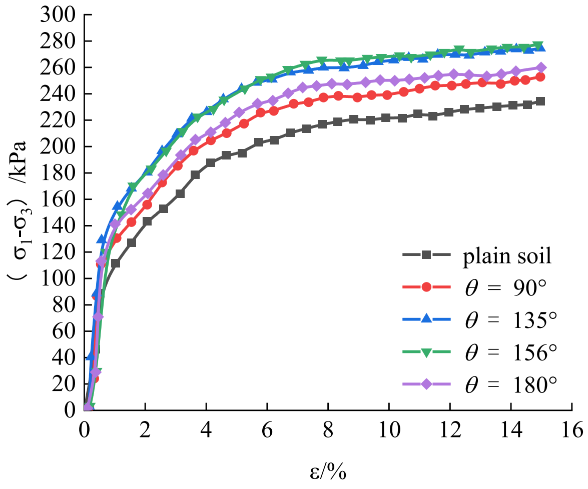
4.2 Numerical Analysis

The safety factor of the slope stability was calculated by finite element strength reduction method (Chen et al. 2014). Accuracy of calculation depends on striping the slope soil and root material embedded into a plurality of units. The cohesive force and intrinsic friction angle of the slope soil will be gradually reduced by means of setting the field variable. The parameters obtained from laboratory tests were used for 2D numerical analysis to evaluate the effects of roots on slope safety as Table 3.

In the process of calculation, the safety factor mainly depends on the yield criterion selected. There are three commonly criteria used to distinguish: the instability, namely, no convergence of finite element calculation, abrupt displacement of characteristic position and transfixion of plastic zone. In order to



(a) σ_3=50kPa (b) σ_3= 100kPa



(c) σ_3= 150kPa

Fig. 7 Stress–strain curves of soil samples with different confining pressures

Table 2 The increment of shear strength parameters of the root reinforced soil samples

Root angle across a potential slip surface θ/°	Cohesion/kPa	Intrinsic friction angle/°	Δc/kPa	$\Delta \varphi$/°
No roots	12.29	23.68	–	–
90	18.41	24.08	6.12	0.40
135	20.86	24.53	8.57	0.85
156	22.08	24.89	9.79	1.21
180	19.87	24.12	7.58	0.44

facilitate the analysis of slope stability, the method of instability discrimination was adopted to calculate the safety factor of slope stability. Eventually, the safety factor of bare soil slope and planted slopes with root system forming different inclinations to the shear surface (θ) were obtained as shown in Table 4.

The stresses and displacements of the bare slope and the planted slopes were obtained by numerical calculation. The partial displacement and stress field cloud diagram were shown in Fig. 9.

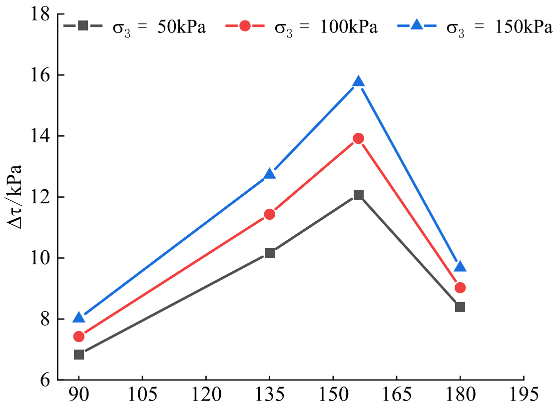


Fig. 8 Effect of root system with different θ on the $\Delta\tau$

Results show the vegetated slopes are significantly more stable than the bare slope. It can be seen from Table 4 and Fig. 9 that the safety factors of slopes with different root angles crossing surface of slide are as follows: $K_{\theta=90^\circ} < K_{\theta=180^\circ} < K_{\theta=135^\circ} < K_{\theta=156^\circ}$. When the roots are at an angle of 156° with the shear surface, the safety factor of the slope work relatively better. The results show that there is no obvious difference in stress aspect between bare slope and planted slope. However, the maximum displacement of root-permeated soil is significantly reduced compared with bare slope. When the roots of vetiver and the shear surface are at an angle of 156°, the displacement of the slope reaches the minimum as showed in Table 5 and Fig. 10.

This is also consistent with the conclusions obtained from the shear tests in laboratory mentioned above. At the same time, it is found that the influence of the root system on the horizontal displacement of the shallow soil is more significant than the vertical displacement under the same conditions. Therefore, the slope soil embedded roots will be more conducive to the stability of the horizontal direction of the slope.

Table 4 Safety factors of slopes with different θ

Root angle/°	no roots	90	135	156	180
Safety factor	1.148	1.236	1.249	1.253	1.246

5 Conclusions

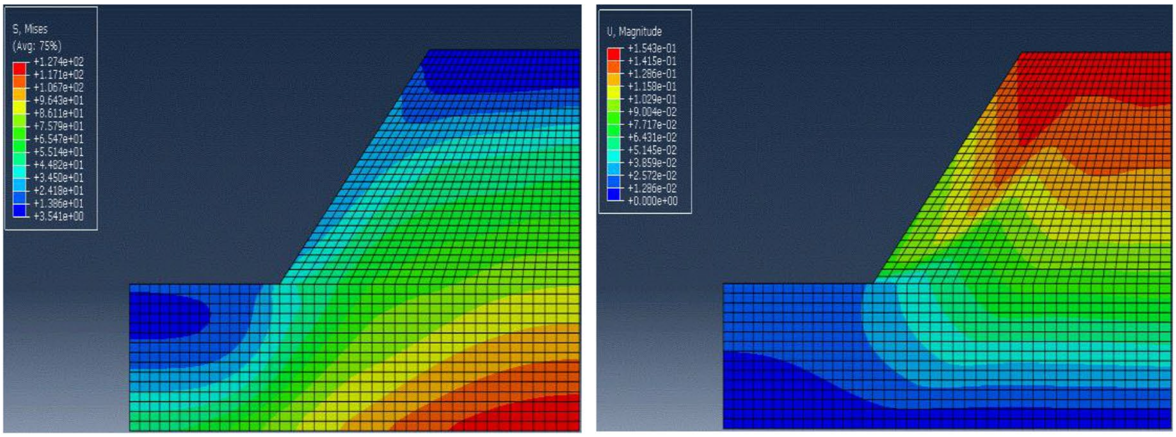
The root of plants usually has a positive effect on mechanical characteristics due to reinforcement action. The root morphology plays an important role in increasing the shear strength of soil. This paper has demonstrated the specific role of vegetation in soil reinforcement applications by means of triaxial tests and finite element method. The stability of planted slope is enhanced compared with bare slope, which highlights the vital importance of slope to prevention of shallow landslides. The following conclusions can be drawn:

(1) A series of triaxial tests were carried out to get the shear strength of no rooted soil and root-permeated soil. It demonstrates that the root system of vetiver has a great effect on the cohesion of soil, but less influence on the intrinsic friction angle.

(2) The formula for calculating the safety factor of slope considering the distribution angle of plant roots is derived theoretically. The cohesive force of the rooted soil was deduced that it will reach the maximum when the roots are oriented angle of $180^\circ - \varphi$ with the potential slip surface, which makes the safety factor of slope maximum.

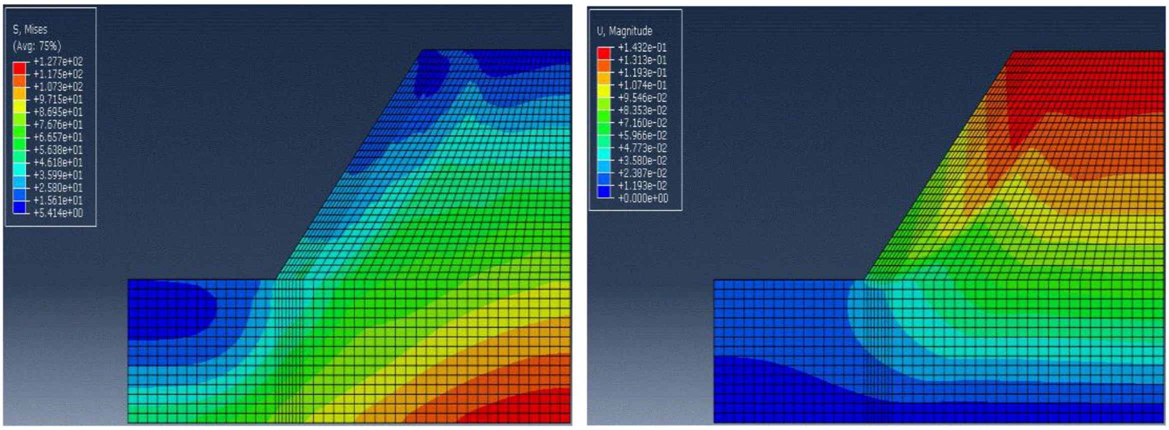
Table 3 Material model parameters for the numerical simulation

Angle of roots crossing the failure surface/°	Elasticity modulus /MPa	Poisson Ratio	Density /(g cm^{-3})	Intrinsic friction angle/°	Cohesion/kPa
No roots	50	0.3	1.82	23.68	12.29
90				24.08	18.41
135				24.53	20.86
156				24.89	22.08
180				24.12	19.87



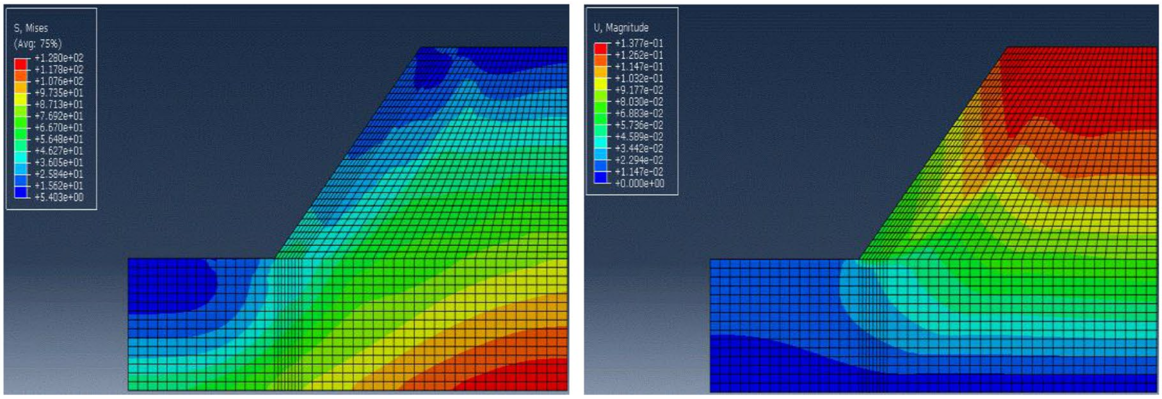
(a) Stress diagram of slope without roots

(b) Displacement diagram of slope without roots



(c) Stress diagram of slope with roots inclination of 90°

(d) Displacement diagram of slope with roots inclination of 90°



(e) Stress diagram of slope with roots inclination of 156°

(f) Displacement diagram of slope with roots inclination of 156°

Fig. 9 The partial stress and displacement fields nephogram of slope with different θ

Table 5 Stress and displacement of slope with different θ

Root angle/°	Maximum stress/kPa	Maximum displacement/mm	Maximum change of stress/kPa	Maximum displacement reduction/mm
No roots	127.4	154.3	–	–
90	127.7	143.2	0.3	11.1
135	128.0	137.9	0.6	16.4
156	128.0	137.7	0.6	16.6
180	127.9	140.7	0.5	13.6

(3) Compared with bare slope, the shear strength of rooted soil is increased significantly. In this study, for the natural slope of 45°, the effect of root reinforcement is different with inclination angles on stability of slope soil. Owing to the intrinsic friction angle was obtained as 24° in laboratory, the increase of shear strength of root-soil is relatively larger when the roots are oriented at an angle of 156° with the potential slip surface.

(4) The numerical calculation model of slope with vegetation roots was established, and the stability of slope was analyzed by using finite element method, which investigated the effect of the vegetation roots on the stability of slope. It is also certified that the horizontal displacement is more significant than the vertical displacement in slope with root.

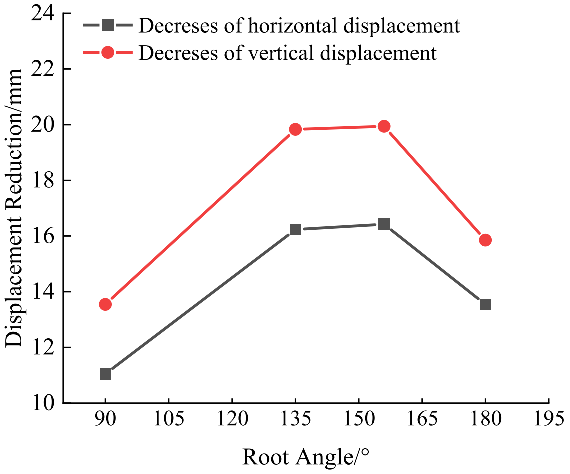


Fig. 10 Effect of root system with different θ on the displacements of slope

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Author Contributions ZL proposed experimental ideas and suggested the drafting of the manuscript. SY and JL participated in model tests and recorded test data. MW wrote manuscripts.

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Data Availability The test model of this article is designed by the author. The data used in the manuscript are all obtained by experiments with authenticity and validity.

Code Availability Not applicable.

Declarations

Conflict of interest The authors declare that they have no conflict of interest with this work. We declare that there are no commercial or associative interests that represent a conflict of interest in connection with the work submitted.

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