

Investigating the Effect of Direction of Grass Roots on Shear Strength of Soil and Stability of Embankment Slope



Jakob Schallberger and Lalita Oka 

Abstract The use of grass to protect the slopes from erosion of road embankments is a common practice. However, quantifying the changes in shear strength of such bio-structured (with grass roots) soil is a complex procedure. One of the important factors affecting the shearing resistance of such soils is the direction of grass roots with respect to the slope angle. An experimental investigation was taken up to quantify the changes in shear strength of soil due to the direction of grass roots. Direct shear tests were conducted on field samples from a slope with grass roots and compared with remolded samples without roots. The field samples were obtained by pushing the samplers in a sloping ground in vertical, horizontal, and in 45 ° inclination. Direct shear tests were conducted on these samples by keeping the direction of the roots in perpendicular, parallel, and inclined to the failure plane during the direct shear test. Thirty-five samples were tested with in-situ moisture content, and fifteen samples were tested in saturated conditions. For the samples tested with in-situ moisture conditions, the test results indicate that the soil with the vertical and inclined root direction experienced a similar overall increase in cohesion and a near negligible change in friction angle. However, the samples with roots parallel to the failure plane experienced the least increase in cohesion in comparison with the other two root directions. A similar trend was observed for the samples tested in saturated conditions. Additionally, slope stability analysis was performed using software SLIDE (version 7) to determine the effects of the root direction on the factor of safety.

Keywords Slope stability · Grass roots · Shear strength

1 Introduction and Background

Maintaining the stability of embankments is one of the important concerns of all road transportation and infrastructure development projects. Road embankments

J. Schallberger · L. Oka (✉)
California State University, 2320 E San Ramon Ave, Fresno, CA 93740, USA
e-mail: loka@csufresno.edu

and retaining walls are typically constructed using granular soils to avoid excessive buildup of pore pressure. However, these soils lack cohesive properties and are susceptible to slope failure. Improving the shear strength of such cohesionless soils is, therefore, a big challenge. While geotextiles are widely used to protect and strengthen the slopes, they are sometimes cost-prohibitive and require regular maintenance. These considerations are especially important for roads located in remote regions. Using plant roots or grass roots to stabilize the slopes is one of the cost-effective solutions. However, predicting the response of such root-reinforced soils is challenging, mostly due to the unknown soil behavioral model. Multiple studies in the past have reported that root-reinforced sandy soils have higher shear strength in comparison with sands without roots (Cazzuffi et al. [1], Comino, and Druetta [2], Eab et al. [3], Fan and Su [4]). Several factors, e.g., root diameter, root tensile strength, and planting density, were found to affect the shear strength of root-reinforced soils (Loades et al. [5]). Effect of Vetiver grass roots on shear strength parameters have been extensively studied by many researchers (e.g., Eab et al. [3], Xu et al. [6], Hamidifar et al. [7]). These researchers have shown a clear evidence of improvement in shear strength and thus improved sliding resistance capacity. While most of these studies were conducted using direct shear tests, it has a major disadvantage of forcing the sample to shear in a horizontal direction. Thus, the direction of the roots with respect to the shearing plane can affect the results. Unfortunately, the problem is further compounded since the existing standardized testing procedure for the direct shear test, ASTM-D-3080 [8], does not include information on the testing procedure for root-reinforced soils. Therefore, this investigation was prompted by the need for more research on the effect of root direction on the shear strength of root-reinforced soils. The soil specimens were obtained from a grass root-reinforced slope by pushing samplers in three directions (vertical, horizontal, and inclined to the slope) to capture the effect of root direction, and direct shear tests were conducted in the laboratory. This paper describes the sampling method and results from the tests. A sample slope stability analysis using software SLIDE (version-7) is also presented.

Use of root-reinforced soil to improve slope stability has been in practice since the thirteenth century (Cazzuffi et al. [1]), but the geotechnical testing of such soils was introduced by the researchers Endo and Tsuruta [9], and Wu et al. [10] in the late twentieth century. Wu et al. [10] and Waldron and Dakessian [11] were among the early researchers to propose the use of Mohr–Coulomb model to estimate the shear strength of root-reinforced soil, and it is still in practice. Recently, some studies (e.g., Cazzuffi et al. [12]) have focused on evaluating the effect of grass species, and soil types and some (e.g., Ji et al. [13], Zhou et al. [14]) have investigated the effects of large root system such as tree roots on the shear strength of the soil.

While there are instances of using triaxial test to measure the shear strength of root-reinforced soils (Zhang et al. [15], Mazzuoli et al. [16]), most studies reported in the literature are based on direct shear tests. This is mainly because of ease in sample preparation; and no difference was found in the end results with remolded specimens (Castellanos and Brandon [17]). However, one of the important drawbacks of the direct shear test is that it forces the failure plane to be horizontal. Although Fitz et al. [18] have documented the role of the direction of failure plane on slope

stability, it is rarely considered in the testing of sands since it is very difficult to obtain undisturbed samples in the sand. Hence, there is evidence in the literature that the direction of roots could play an important role in determining the shear strength of root-reinforced soils, and it will ultimately influence slope stability analyses for the road embankments. A study was therefore undertaken to investigate the effect of root orientation on shear strength of sandy soil and the factor of safety estimation for a slope.

2 Testing Program

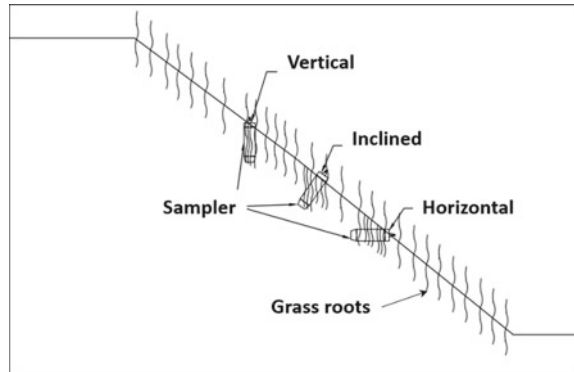
2.1 Field Sampling

The sampling site was located between the Laton and Riverdale towns in the Fresno County of Central California. Figure 1 shows the details of field measurements and sample collection. The slope profile was determined by staking along the length of slope and measuring the elevations with the help of Zipline Pro-2000 high precision altimeter. A split sampler drive tube consisting of two 6-inch-long samplers was pushed in the sloping ground (covered with grass) with the help of slide hammer. After retrieving the samplers, both ends were covered with plastic caps to retain the moisture content. Additionally, one borehole was drilled to a depth of 35 ft. below the top of the basin for soil profile to be used in the numerical model.



Fig. 1 Site location and details of field sampling: **a** grass root-reinforced slope, **b** slope length measurement, **c** altimeter, **d** sampling split mold

Fig. 2 Schematic representation of orientation of grass roots during sampling



To overcome the difficulty due to forced horizontal plane during the direct shear test, the soil samples from a natural root-reinforced slope were collected in three directions (vertical, horizontal, and inclined). Figure 2 shows a schematic representation of the orientation of grass roots during sampling. A total of sixty samples were collected from ten locations along the slope consisting of two samples in each direction.

2.2 Laboratory Testing

The field samples consisting of root-reinforced soil were brought back to the laboratory. The laboratory testing consisted of measuring unit weight (ASTM-D-7263 [19]), moisture content (ASTM-D-2216 [20]), particle size distribution (ASTM-D-6913 [21]), organic content determination (ASTM-D-2974 [22]), and direct shear tests (ASTM-D-3080 [8]) to measure the shear strength parameters (c' and ϕ'). The diameter of each sample was 2.42 inches. A minimum of three direct shear tests with the normal stress increments of 1 ksf, 2 ksf, and 3 ksf were conducted on each directional sample from each sampling location. The rate of shearing was 0.03 inch/min. Figure 3 shows the direct shear test setup and the direction of shearing

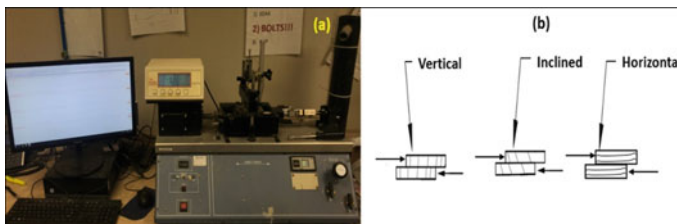


Fig. 3 Direct shear tests: **a** test setup, **b** orientation of grass roots

plane with respect to root orientation. A total of 35 samples were tested under in-situ moisture condition, and 25 samples were tested under the saturated condition to capture the effect of saturation on shear strength parameters. Direct shear tests were also conducted on remolded samples without roots with in-situ moisture content and under the saturated condition for comparison.

3 Results and Discussions

Table 1 shows the average index properties of the soil, including organic content, which is the ratio of the weight of roots to the weight of soil solids. It is important to note that all the soil samples revealed that the field slope consisted of sandy soil with USCS classification being SP-SM (poorly graded sand with silt). As mentioned earlier, each set of the direct shear test consisted of fixed normal stress increments (1 ksf, 2 ksf and 3 ksf). Figure 4 shows the typical direct shear test data for one set of samples. The combination of peak shear stress (τ_{max}) and corresponding normal

Table 1 Index properties of the soil

Soil properties	Orientation of roots		
	Vertical	Horizontal	Inclined
Dry unit weight (lb/ft ³)	99	97.7	99.5
Organic content (%)	0.8	0.7	0.7
Fines content (%)	13.3	11.4	10.9
Plasticity of fines	Non-plastic	Non-plastic	Non-plastic
Soil classification (As per USCS)	SP-SM	SP-SM	SP-SM

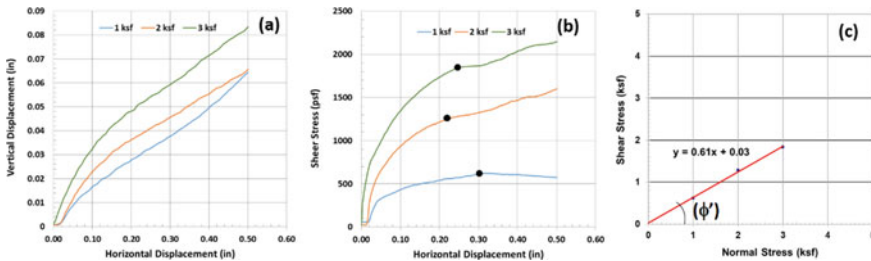


Fig. 4 Typical direct shear test result: **a** vertical displacement versus horizontal displacement, **b** shear stress versus horizontal displacement, **b** mohr–Coulomb failure envelope

stress (σ) was then selected to develop Mohr–Coulomb failure envelope. The angle of internal friction (ϕ') and cohesion (c') was thus estimated for each set of samples.

Figure 5 shows the comparison between the displacement response of the soils with and without grass roots. Inclusion of roots was found to show increased horizontal displacement than soils without roots. Thus, roots were found to make the soil more ductile and thus improved resistance for cracking which typically is a sign of brittleness. Similar behavior is noted by multiples studies (e.g., Comino and Druetta [23]) in the past.

Figure 6 shows the comparison of displacement based on root direction for a typical specimen. It was observed that soils with inclined root orientation experienced more horizontal displacement (ductility) in comparison with horizontal and vertical root orientations. This clearly shows that direction of root influences the deformations that the soil might undergo.

Figure 7 shows shear strength parameters based on the inclusion of grass roots as well as the saturation condition of the test specimens. Figure 7a, c shows that

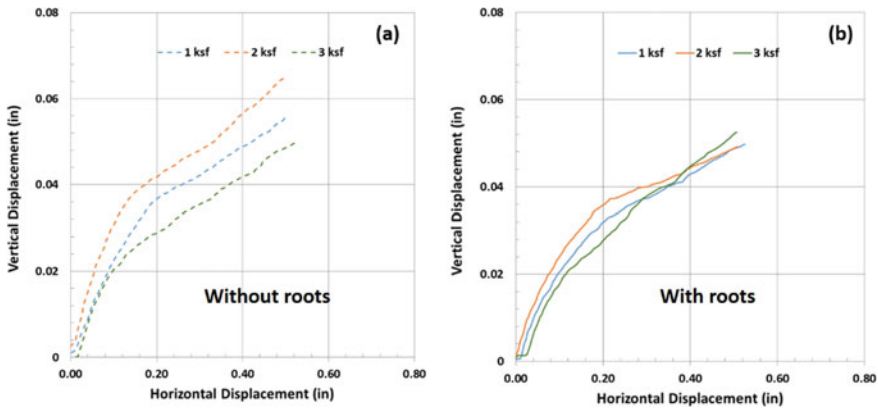


Fig. 5 Comparison of displacements during direct shear tests: **a** for soils without roots, and **b** for soils with roots

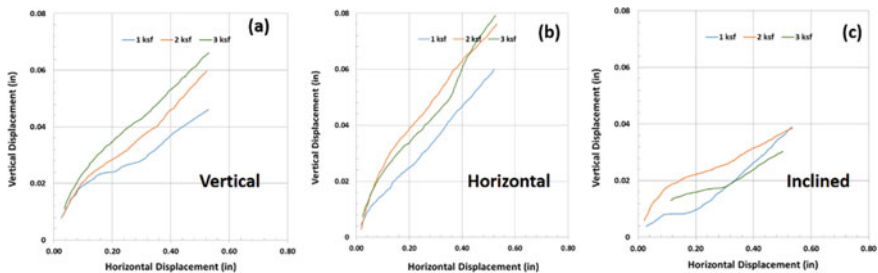


Fig. 6 Comparison of displacements during direct shear tests based on root orientation: **a** for soil with vertical root orientation, **b** for soil with horizontal root orientation, and **c** for soil with inclined root orientation

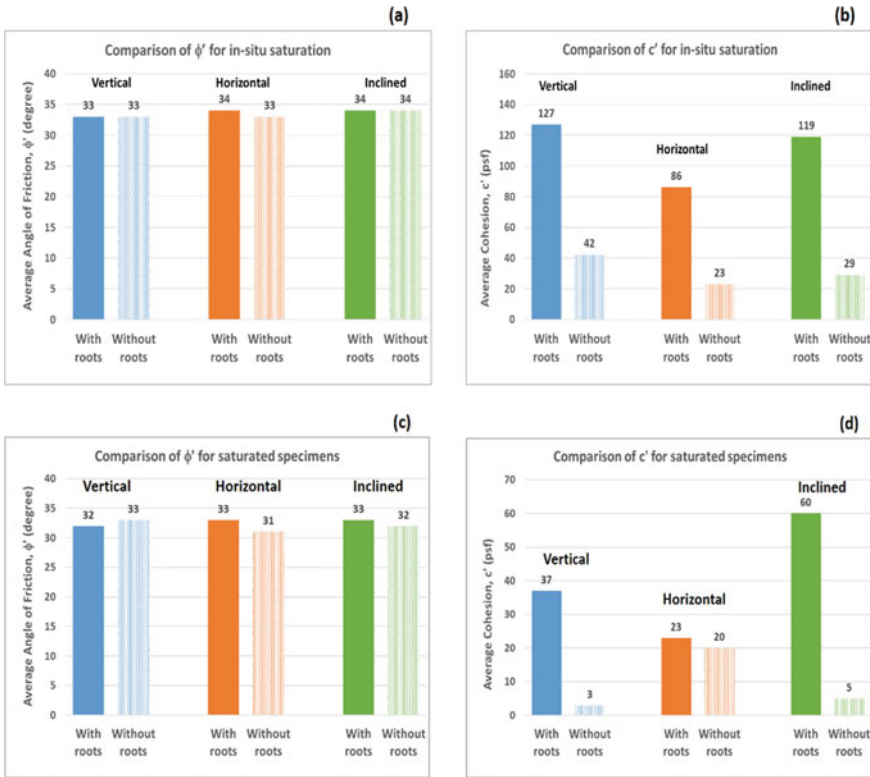


Fig. 7 Comparison of shear strength parameters: **a** ϕ' at in-situ saturation, **b** c' at in-situ saturation, **c** ϕ' at 100% saturation, **d** c' at 100% saturation

angle of friction (ϕ') generally remained unaffected irrespective of changes in root direction or saturation condition, while Fig. 7b and d shows that soils with roots generally experienced increased cohesion in comparison with soil without roots. These findings are similar to the previous studies by Mickovski and Beek [24], and Xu et al. [6]. Additionally, as per Fig. 7b, when tested with in-situ moisture content (partially saturated), soil containing vertical root reinforcement developed the maximum cohesion (127 psf) while soil containing horizontal roots developed the least cohesion (86 psf). On the other hand, Fig. 7d shows that when tested under fully saturated condition, the soil with inclined roots developed the highest (86 psf) cohesion while soil with horizontal roots experienced the least cohesion (23 psf). Figure 7b and d also indicates that cohesion decreased with an increase in saturation. This phenomenon can be attributed to the addition of suction due to the presence of roots. Interestingly, the unsaturated soil specimens with inclined root orientation experienced the highest (310%) increase in cohesion in comparison with unsaturated soils without roots. For the fully saturated samples, the soil specimens with vertical root mobilized the highest (1133%) increase in cohesion in comparison with saturated

soils without roots. Figure 7b and d also indicates that although the specimens with roots in the horizontal direction (parallel to the direction of the shearing plane) did experience an increase in cohesion, their percent increase was least when tested under fully saturated condition. Changes in cohesion are summarized in Table 2.

The findings of this study can be effectively applied in slope stability analysis in engineering practice, which consists of determining the factor of safety using the limit equilibrium method. In the case of finite slopes such as road embankments, the factor of safety estimate is based on moment equilibrium of sliding slices or wedges of soil under the slope. Thus, the factor of safety is given by the equation:

$$F_s = \frac{\sum M_R}{\sum M_D} = \frac{\sum c'l_a + \tan \phi' N'}{\sum W \sin \alpha} \quad (1)$$

where M_R is the resisting moment and M_D is the driving moment. c' and ϕ' are the cohesion and angle of internal friction of the soil, l_a is the length of arc, ($N' = W \cos \alpha$) and ($W \sin \alpha$) are the normal and tangential components of the weight of the sliding wedge of soil, and α is the radial angle. The critical factor of safety is typically determined iteratively by considering slip surfaces passing through sloping ground. These iterations can easily be performed using any commercially available software. Figure 8 shows computation of the factor of safety using the software, SLIDE (version 7) for slope without grass roots and with grass roots in the vertical direction. The slope profile was constructed using soil properties from this study. The strength parameters of the soil were modeled in the software using the anisotropic function. This function allows the user to input strength parameters depending on how the failure plane passes through the soil with grass roots. The failure plane represents the shear plane in laboratory testing. Therefore, the vertical, horizontal, and inclined directions were all considered in the model for determining factor of safety. Figure 8a and b displays the anisotropic function input parameters. Horizontal, inclined, and vertical sample strength parameters were input from 0° to 10° , 10° to 80° , and 80° to 90° , respectively. These values are mirrored in the circle for any other failure plane beyond 0° to 90° . Figure 8c and d shows the estimation of factor of safety for slopes with and without grass roots, respectively. Based on the field observations, the roots were assumed to be present only in the top one-foot thick layer. It is, however, entirely possible to have deeper roots depending on species of grass. In this example, the critical factor of safety for slope without grass roots was found to be 1.266, while the critical factor of safety for the slope with grass roots in the vertical direction was found to be 1.327, which is approximately 5% higher than the slope without grass roots. A similar increase in the factor of safety was previously reported by Eab et al. [3], Lin et al. [25], and Liu et al. [26]. Although the numerical model predicted a modest increase in factor of safety, the purpose of this example was to show that numerical tools can easily be applied to predict the behavior of slope with grass roots. By tactically arranging the root reinforcement, practicing geotechnical engineers can easily quantify the differences and recommend slope protection measures.

Table 2 Summary of changes in cohesion due to root inclusion

	Vertical root orientation			Horizontal root orientation			Inclined root orientation		
	c' With root (psf)	c' Without roots (psf)	Change in c' (%)	c' With root (psf)	c' Without roots (psf)	Change in c' (%)	c' With root (psf)	c' Without roots (psf)	Change in c' (%)
Unsaturated	127	42	202	86	23	274	119	29	310
Saturated	37	3	1133	23	20	15	60	5	1100

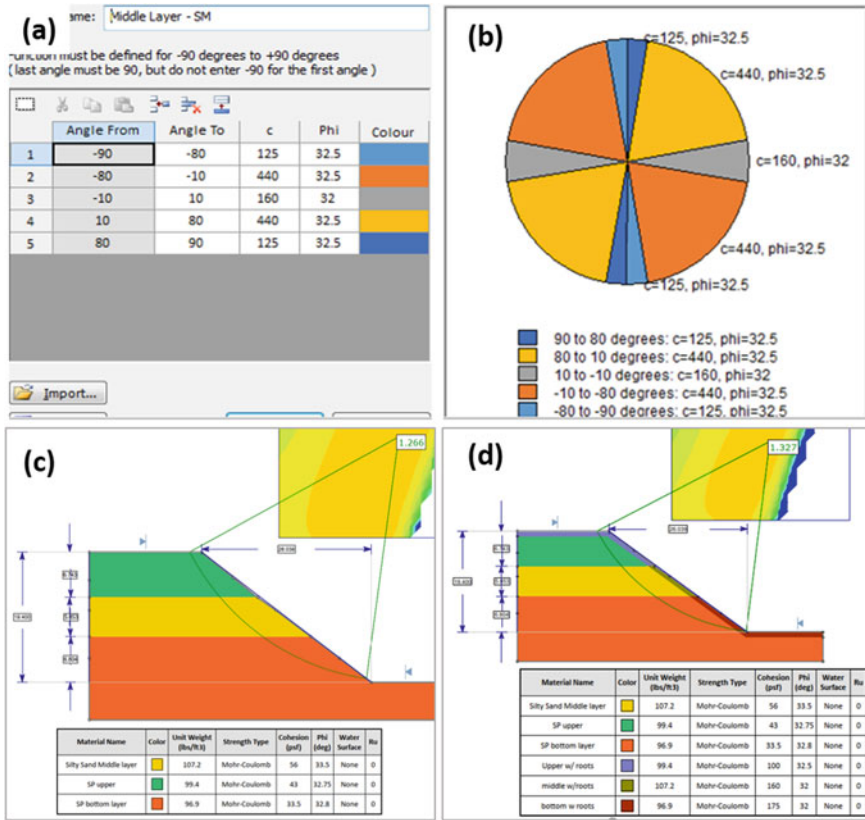


Fig. 8 Slope stability analysis using Slide (version 7): **a** entering anisotropic function, **b** assigning values of anisotropic shear strength parameters, **c** estimating factor of safety for slope without grass roots, and **d** estimating factor of safety for slope with grassroots in the vertical direction

4 Conclusions

- An experimental study was undertaken to investigate the effect of root orientation on the shear strength parameters of soil.
- Field samples were collected with vertical, horizontal, and inclined root orientation, which enabled direct shear tests to be performed by keeping root orientation perpendicular, parallel, and inclined to the shearing plane, respectively.
- While root orientation did not affect the angle of internal friction (ϕ') of the soils, the development of cohesion (c') was considerably affected by root orientation. The samples with the root orientation perpendicular to the shearing plane were found to mobilize the highest cohesion while root orientation parallel to the shearing plane mobilized the least amount of cohesion.
- Soils with inclined root orientation showed more ductility in comparison with soils consisting of vertical and horizontal root orientations.

- A numerical model incorporating improved soil properties for the surface layer predicted a modest (5%) increase in factor of safety for the vertically root-reinforced slope in comparison with a slope without root reinforcement.

Acknowledgements The authors would like to thank BSK Associates, Fresno for their generous support especially with field sampling and laboratory testing. Additionally, the authors would like to thank Mr. Degol Messfin for providing help in conducting laboratory tests. The authors are also thankful to the reviewers for their constructive comments that helped improve the paper.

References

1. Cazzuffi D, Cardile G, Giofrè D (2014) Geosynthetic engineering and vegetation growth in soil reinforcement applications. *Transp Infrastruct Geotechnol* 1:262–300
2. Comino E, Druetta A (2010) The effect of poaceae roots on the shear strength of soils in the Italian alpine environment. *Soil Tillage Res* 106:194–201
3. Eab KH, Likitlersuang S, Takahashi A (2015) Laboratory and modelling investigation of root-reinforced system for slope stabilisation. *Soils Found* 55:1270–1281
4. Fan C-C, Su C-F (2008) Role of roots in the shear strength of root-reinforced soils with high moisture content. *Ecol Eng* 33:157–166
5. Loades K, Bengough A, Bransby M, Hallett P (2010) Planting density influence on fibrous root reinforcement of soils. *Ecol Eng* 36:276–284
6. Xu L, Gao C, Yan D (2018) Interaction between vetiver grass roots and completely decomposed volcanic tuff under rainfall infiltration conditions. *Geofluids*
7. Hamidifar H, Keshavarzi A, Truong P (2018) Enhancement of river bank shear strength parameters using vetiver grass root system. *Arab J Geosci* 11:611
8. ASTM-D-3080–11 (2011) Standard Test Method for Direct Shear Test of Soils Under Consolidated Drained Conditions, in, ASTM International, PA, pp 1–9
9. Endo T, Tsuruta T (1969) The effect of the tree's roots on the shear strength of soil, Annual Report, 1968, Hokkaido Branch, For. Exp. Stn., Sapporo, Japan, pp 167–182
10. Wu TH, McKinnell WP III, Swanston DN (1979) Strength of tree roots and landslides on Prince of Wales Island Alaska. *Canadian Geotech J* 16:19–33
11. Waldron L, Dakessian S (1981) Soil reinforcement by roots: calculation of increased soil shear resistance from root properties. *Soil Sci* 132:427–435
12. Cazzuffi D, Corneo A, Crippa E (2006) Slope Stabilisation by perennial “gramineae” in Southern Italy: plant growth and temporal performance. *Geotech Geol Eng* 24:429–447
13. Ji J, Kokutse N, Genet M, Fourcaud T, Zhang Z (2012) Effect of spatial variation of tree root characteristics on slope stability. A case study on Black Locust (*Robinia pseudoacacia*) and *Arborvitae* (*Platycladus orientalis*) stands on the Loess Plateau, China, *Catena*, 92:139–154
14. Zhou Y, Watts D, Cheng X, Li Y, Luo H, Xiu Q (1997) The traction effect of lateral roots of *Pinus yunnanensis* on soil reinforcement: a direct in situ test. *Plant Soil* 190:77–86
15. Zhang C-B, Chen L-H, Liu Y-P, Ji X-D, Liu X-P (2010) Triaxial compression test of soil–root composites to evaluate influence of roots on soil shear strength. *Ecol Eng* 36:19–26
16. Mazzuoli M, Bovolenta R, Berardi R (2016) Experimental investigation on the mechanical contribution of roots to the shear strength of a sandy soil. *Procedia Engineering* 158:45–50
17. Castellanos B, Brandon T (2013) A comparison between the shear strength measured with direct shear and triaxial devices on undisturbed and remolded soils. In: *Proceedings of the 18th international conference on soil mechanics and geotechnical engineering*, Paris, pp 317–320
18. Fitz GM, Brandon TL, Duncan JM (1992) Back analysis of olmsted landslide using anisotropic strengths, transportation research record

19. ASTM-D-7263–18 (2018) Standard test methods for laboratory determination of density (Unit Weight) of soil specimens, in, ASTM International, PA
20. ASTM-D-2216–19 (2018) Standard test methods for laboratory determination of water (moisture) content determination of soil and rock by mass, in, ASTM international, PA
21. ASTM-D-6913–14 (2014) Standard test methods for particle-size distribution (gradation) of soils using sieve analysis, in, ASTM International, PA
22. ASTM-D-2974–14 (2014) Standard test methods for moisture, ash, and organic matter of peat and other organic soils, in, ASTM international, PA
23. Comino E, Druetta A (2009) In situ shear tests of soil samples with grass roots in Alpine environment. *Am J Environ Sci* 5:475
24. Mickovski S, Van Beek L (2009) Root morphology and effects on soil reinforcement and slope stability of young vetiver (*Vetiveria zizanioides*) plants grown in semi-arid climate. *Plant Soil* 324:43–56
25. Lin D-G, Huang B-S, Lin S-H (2010) 3-D numerical investigations into the shear strength of the soil–root system of Makino bamboo and its effect on slope stability. *Ecol Eng* 36:992–1006
26. Liu HW, Feng S, Ng CWW (2016) Analytical analysis of hydraulic effect of vegetation on shallow slope stability with different root architectures. *Comput Geotech* 80:115–120