The mechanism of the plant roots′ soil-reinforcement based on generalized equivalent confining pressure

Ping Guo Equal first author, 1, 2 , **Zhenyao Xia** Equal first author, 1, 2 , **Qi Liu** [3] , **Hai Xiao** Corresp., 1, 2 , **Feng Gao** [1] , **Lun Zhang** [1] , **Mingyi Li** [1, 2] , **Yueshu Yang** [1, 2] , **Wennian Xu** [1, 2]

[1] Key Laboratory of Geological Hazards on Three Gorges Reservoir Area (China Three Gorges University), Ministry of Education, Yichang, China

[2] Engineering Research Center of Eco-environment in Three Gorges Reservoir Region, Ministry of Education, China Three Gorges University, Yichang, China

[3] Key Laboratory of Mountain Hazards and Earth Surface Process, Institute of Mountain Hazards and Environment, CAS, Chengdu, China

Corresponding Author: Hai Xiao
Email address: oceanshawctgu@163.com

Background: To quantitatively evaluate the contribution of plant roots on soil shear strength, a new aspect of generalized equivalent confining pressure (GECP) was considered in the terms of the function of plant roots in the reinforced soil was equivalent to confining pressure.

Methods: In this paper, silt loam soil was selected as the test soil, and the roots of *Indigofera amblyantha* were chosen as the reinforcing material. Different drainage conditions (consolidation drained (CD), consolidation undrained (CU), unconsolidation undrained (UU)) were launched to analyze the influences of different root distribution patterns (orizontal root (HR), vertical root (VR), complex root (CR)) and root contents (0.25%, 0.50% , 0.75%) on the shear strength of soil-root composites.

Results: The triaxial test results showed that under the CD and CU conditions, GECP of 0.75% root content in soil-root composites is 1.5-2.0 times that of 0.50% and more than 5 times that of 0.25%.GECP of CR is 1-2 times that of VR and 2-5 times that of HR. GECP of plant roots augmented by 20%-50%, when confining pressure increased from 50 kPa to 150 kPa. A complicated variation in GECP was observed under the UU condition, when root content is low, GECP of plant roots is minus and decreased as confining pressure increased.

Conclusion: It was concluded that the evaluation mechanism of plant roots’ soil-reinforcement based on GECP is considerably adaptive to measure the influences of roots on soil under different drainage conditions and root characteristics.

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[1] Key Laboratory of Geological Hazards on Three Gorges Reservoir Area (China Three Gorges University), Ministry of Education, Yichang 443002, People's Republic of China

[2] Engineering Research Center of Eco-environment in Three Gorges Reservoir Region, Ministry of Education, China Three Gorges University, Yichang 443002, People's Republic of China

[3] Key Laboratory of Mountain Hazards and Earth Surface Process, Institute of Mountain Hazards and Environment, CAS, Chengdu 610041, People's Republic of China

Corresponding author:

Hai Xiao

No.8 Daxue road, Xiling district, China Three Gorges University, Yichang City, Hubei Province, 443002, People's Republic of China.

E-mail address: oceanshawctgu@163.com (Hai Xiao)

* These authors contributed equally to this work, Zhenyao Xia is a co-first author.

ABSTRACT

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Keywords soil-root composite, shear strength indexes, generalized equivalent confining pressure, drainage condition, root characteristics

INTRODUCTION

Plant roots play an important role in improving the overall stability of slope superficial soil and increasing the safety coefficient of the slope (*Zegeye et al., 2018; Zhou & Wang, 2019*). Plant roots system is a complex dynamic system, for which non-destructive monitor implemented is difficult, so it is always a tricky part in the research field regarding the mechanism of plant roots' soil-reinforcement.

At present, the evaluation mechanism of slope vegetation protection mainly includes mechanical and hydraulic mechanisms (*Gonzalez-Ollauri & Mickovski, 2017; Feng, Liu & Ng, 2020*). Based on both mechanisms, three vegetation protection theories were proposed, namely, the mechanical reinforcement of plant roots (*Jin et al., 2019*), the excess pore-water pressure in soil is dissipated by root water uptake (*Liu, Feng & Ng, 2016*) and soil matric suction is induced via plant transpiration (*Ng et al., 2013; Gadi et al., 2019*). The most conspicuous source that vegetation enhances slope stability is root reinforcement.

The effect of root reinforcement on slope stability can be evaluated directly in terms of the additional shear strength provided by plant roots in reinforced soil. To analyze the effect of plant roots on slope stability, many in-situ and laboratory tests were carried out on the vegetated soil (*Wu & Watson, 1998; Operstein & Frydman, 2000*), and the corresponding analytical models for soil-root composites have also been developed (*Waldron, 1977; Waldron & Dakessian, 1981; Wu et al., 1988*). For example, a linear equation of root population density and soil shear strength was obtained (*Endo & Tsurnta, 1969*), and c extend to the sliding layer have a stable effect on shallow slopes by in-situ shear tests (*Gray & Ohashi., 1983; Greenway, 1987*).

In addition, some mechanistic models have also been developed to evaluate the additional shear strength provided via plant roots (*Wu, 1976; Waldron, 1977; Wu, McKinell $ Swanston, 1979; Gray & Sotir, 1998*). However, some researchers have reached the consensus that the Wu-Waldron model is potentially a significant overestimate of actual cohesion of soil-root composites (*Waldron & Dakessian, 1981; Operstein & Frydman, 2000; Pollen & Simon, 2005*). *Schwarz et al. (2010)* proposed that the correction factor of Wu-Waldron model in the range of 0.34-0.50 for roots of herbs and shrubs. In addition, the Wu-Waldron model or the modified model is derived based on the assumption that plant roots are elastic, initially oriented perpendicular to the shear surface and the friction angle of soil is unaffected by plant roots (*Waldron, 1977; Greenway, 1987*).

Shallow landslides present a highly consistent with rainfall, so rainfall is considered as the major cause for slopes instability. Decisive factors controlling shallow landslides are mechanical properties of sloping soil mass, frequency and duration of rainfall, and plant species (roots morphology) (*Matsushi, Hattanji & Matsukura, 2006; Normaniza, Faisal & Barakbah, 2008*). Rainfall infiltration in slopes induces an increase in soil moisture content, whereas the effect of plant roots on the shear strength of vegetated soil with a significant decrease (*Normaniza &Barakbah, 2006; Jiang, Dong & Wang, 2009*).

Based on the fact that the differences in depth, soil moisture content and root characteristics may result in a substantial change in soil shear strength. The effect of plant roots in reinforced soil is understood as an additional confining pressure to the soil in the traditional equivalent confining pressure. Therefore, the expression of generalized equivalent confining pressure (GECP) was derived to investigate the influence of root contents and root distribution patterns on the shear strength of reinforced soil under different drainage conditions (consolidation drained (CD), consolidation undrained (CU), unconsolidation undrained (UU)) were launched to analyze the influences of different root distribution patterns (orizontal root (HR), vertical root (VR), complex root (CR)) and root contents (0.25%, 0.50% , 0.75%) in this research.

MATERIAL AND EXPERIMENTAL METHODS

Experimental materials

In this paper, the soil was taken from cutting slope on the first phase urban expressway in Xiazhou avenue in Yichang, China. Test soil was chosen below the surface of 0.3 m, and impurities in the soil were removed. The soil was air-dried, crushed and sieved through a 2.0 mm sieve. The soil had a silt loam texture with 24.08% of sand (0.05-2.00 mm), 55.91% of silt (0.002-0.05 mm), 20.01% of clay (<0.002 mm) content, and 1.38 g cm^{-3} of bulk density, 14.37% of natural moisture content, 2.78% of air dried soil moisture content, 6.2 of pH value.

Indigofera amblyantha, used widely in slope greening projects, which roots were selected as the reinforcing material. *Indigofera amblyantha* belongs to perennial deciduous shrub, its growing period is 6 months approximately, possess strong ability in drought resistance and barren resistance. The plants being mentioned above is the most common soil-water conservation plant in tropical and subtropical regions.

Indigofera amblyantha with a horizontal developed root system, including a lot of the branches and fibrous roots, and the root diameter is mostly concentrated within 1.0-2.5 mm. In this paper, 50 plants of *Indigofera amblyantha* were excavated by the whole excavated method. Normal and straight roots were scissored with scissors based on the length of 30 mm and 60 mm. The roots which the average diameter was 1.4-1.6 mm were chosen, of with the average tensile resistance and the average tensile strength were 62.10 N and 35.86 MPa, respectively.

Experimental methods

The density and the moisture content of soil-root composites were set according to the actual situation of test soil taken from cutting slope (Bulk density is 1.57 g cm^{-3} and natural moisture content is 14.37%). Root contents (Quality percentage: the ratio of the root mass to soil mass in the specimens) were set at 0.25%, 0.50% and 0.75%, respectively.

Soil-root composites were remolded in a circular loading box of Φ 39.1 mm×80 mm which matched with the TSZ-1 strain-controlled triaxial compression apparatus. Firstly, the suitable amount of test soil was weighed and placed in a container which can be sealed, followed by spraying the amount of water on the soil reach the moisture content required in this paper. Secondly, test soil and water were fully mixed, and then the container was sealed for 24 h until test soil was soaked completely. Thirdly, the required amount of soil was taken from the sealed container and placed in the circular loading box mentioned above. Finally, plant roots were buried evenly in the soil and the method of three-layer compaction was adopted to remold soil-root composites in the circular loading box according to the methods of soil mechanics test standardization and specimen preparation. In addition, specimens of un-reinforced soil were also prepared, and preparation processes were consistent with the above, except that no roots were present in the specimens.

Root distribution pattern was divided into three forms, as shown in Fig. 2. The first form (1) is VR, root length is 60 mm; the second form (2) is HR, and the root length is 30 mm; and then the third form (3) is CR, the content of horizontal and vertical roots account for 1/2, respectively. In this paper, plant roots were organized in the center of soil-root composites in three forms.

A prepared specimen was put into the pressure room on which 20 kPa confining pressure was forced. The non-bubble water was entered the specimen base until water overflow from the upper, and the constant head was controlled at 1.2 m. The saturated specimens were obtained when the inflow water and the overflow water was equal. According to the test plan with the same conditions of sample size (Φ 39.1 mm ×80 mm), sample type (Un-reinforced and Reinforced), root content (0.25%, 0.50%, 0.75%), root distribution pattern (HR, VR, CR), confining pressure (50, 100, 150 kPa), and the different condition of shearing rate (0.012 mm min^{-1} for CD, 0.12 mm min^{-1} for CU, 0.9 mm min^{-1} for UU), the shear strengths of soil-root composites and un-reinforced soil specimens were measured by the triaxial test on 15% of axial strain (*Zhang et al., 2010*).

Generalized equivalent confining pressure (GECP)

The GECP was derived from the traditional equivalent confining pressure. *Gray and Al-Refeai (1986)* analyzed the failure mechanism of reinforced sandy soil in triaxial test and derived the expression of traditional equivalent confining pressure under drained condition (*Moroto, 1992; Li et al., 2017)*:

$$\Delta\sigma_{3t} = \sigma_3 \frac{\Delta\sigma_{1f}}{\sigma_{1f}} \tag{1}$$

where σ_3 and $\Delta\sigma_{3t}$ represent respectively confining pressure and traditional equivalent confining pressure, $\Delta\sigma_{1f}$ represent the deviator of failure principal stresses of reinforced and un-reinforced soil specimens under the same confining pressure of σ_3.

$$\Delta\sigma_{1f} = \sigma_{1fb} - \sigma_{1f} \tag{2}$$

where σ_{1f} is the failure principal stress of un-reinforced soil under the confining pressure of σ_3, σ_{1fb} is the failure principal stress of reinforced soil under the confining pressure of σ_3.

The expression of traditional equivalent confining pressure is proposed for sandy soil under the drained condition, in which cohesion have not been considered. The cohesion of sandy soil is 0, but cohesive soil is not, meanwhile, the function of plant root in reinforced soil is evaluated in which don't take the effect of the drained condition into account.

For the above questions, *Huang et al. (2007)* proposed the GECP of cohesive soil and soil-root composite under different drainage conditions, depending on the fact that the Mohr-Coulomb strength theory is also obeyed in reinforced soil. GECP is the deviator of confining pressure between reinforced and un-reinforced soil specimens at the same shear strength (Fig. 1). To distinguish the traditional expression of equivalent confining pressure from generalized equivalent confining pressure, the $\Delta\sigma_{3g}$ represent it below.

The limited balance equation of un-reinforced soil:

$$\sigma_{1f} = \sigma_3 K_p + 2c\sqrt{K_p} \quad (3)$$

The limited balance equation of reinforced soil in terms of un-reinforced according to the deviator of confining pressures between reinforced and un-reinforced soil specimens at the same shear strength:

$$\sigma_{1fb} = (\sigma_3 + \Delta\sigma_{3g})K_p + 2c\sqrt{K_p} = \sigma_{1f} + \Delta\sigma_{3g}K_p \quad (4)$$

where $\Delta\sigma_{3g}$ represent generalized equivalent confining pressure; K_p is the passive earth pressure coefficient of cohesive soil, $K_p = tan^2\left(45^\circ + \frac{\varphi}{2}\right)$; c and φ represent respectively shear strength indexes.

Expression of GECP:

$$\Delta\sigma_{3g} = \sigma_3 \frac{\Delta\sigma_{1f}}{\sigma_{1f} - 2c\sqrt{K_p}} \quad (5)$$

Expression (5) indicates that GECP of soil-root composite depends on the deviator of failure principal stresses of reinforced and un-reinforced soil specimens, the failure principal stress of un-reinforced soil and the shear strength indexes of un-reinforced soil. The expression of traditional equivalent confining pressure is a special case when the cohesion is 0, then the form (5) transform into the form (1). That is the expression of traditional equivalent confining pressure that is proposed for sandy soil, so sandy soil can be regarded as a cohesive soil when cohesion is 0.

TEST RESULTS

Shear strength indexes of soil -root composites under different drainage conditions

Table 1 summarized the shear strength indexes, c and φ, obtained from the triaxial shear test by using the Mohr-Coulomb failure criterion. For the un-reinforced soil, c values were characterized by a decrease followed by an increase under the CD, CU and UU conditions. In addition, φ values were listed at 21.9°, 20.1° and 11.6°, respectively.

Under the CD and CU conditions, c values of soil-root composites increase significantly and φ values remain basically stable compared with un-reinforced soil, with the advance of root content.

Shear strength indexes of soil-root composites increase the most under the CD condition, with a cohesive increment of 251.9% and an internal friction angle increment of 45.2%. On the same condition of root content and drainage condition, shear strength indexes are very low under HR, intermediate for VR and highest for CR.

Under the UU condition, no significant difference is observed in shear strength indexes of soil-root composites when root distribution pattern changing. Thereinto, *c* values present a complicated change trend, which mainly depends on root distribution pattern and root content. For example, when VR in soil-root composites, cohesion decreased from 15.35 kPa to 11.81 kPa due to root content increased (0.25%, 0.50%, 0.75%). However, for HR and CR, cohesion presents a decreasing trend followed by an augment. In addition, φ values of soil-root composites are greater than 11.6 and close to 11.6.

The relationship between GECP of *Indigofera amblyantha* roots in the reinforced soil and root content

Figure 3 showed the relationship between GECP of plant roots in soil-root composites and root content. Under the CD and CU conditions, when root content is 0.75%, GECP of the plant roots in soil-root composites is 1.5-2.0 times that of 0.50% and more than 5 times that of 0.25%. Take the CD condition as an example, when soil-root composites are forced by 150 kPa confining pressure and CR content is 0.75%, GECP of plant roots in soil-root composites is 106.83 kPa （Table 2）. Namely, the shear strength of soil-root composites in the condition is equivalent to the strength of un-reinforced soil that subjected to the confining pressure of 256.83 kPa. For the UU condition, GECP of plant roots mainly concentrated within the range of -10 kPa to 10 kPa. GECP of plant roots presents trend as root content increase largely mirrored those contained in the drainage condition. When CR is placed in reinforced soil, GECP changes from negative to positive as root content increase, whereas GECP is always minus under the condition of HR.

The relationship between GECP of *Indigofera amblyantha* roots in the reinforced soil and drainage condition

The variation trend of GECP resulted from the change of consolidation and drainage condition is observed in Fig. 4. From 3 root distribution patterns perspectives, GECP shows the same phenomenon with the change of consolidation and drainage conditions. That is, GECP increases gradually due to the state changes from UU to CD. Moreover, the effect of root distribution pattern on GECP in reinforced soil followed the sequence of CR > VR > HR. Under the CU and CD conditions, GECP of CR is 1-2 times that of VR and 2-5 times that of HR. The largest GECP of CR is 106.83 kPa, while only 21.26 kPa in HR (Table 2).

The relationship between GECP of *Indigofera amblyantha* roots in the reinforced soil and confining pressure

As shown in Fig. 5, under the CD and CU conditions, GECP of plant roots increases as confining pressure, an extremely significant positive correlation (Sig<0.05) was observed. GECP of plant roots augmented by 20%-50% when confining pressure increased from 50 kPa to 150 kPa. However, a complicated relationship is observed between GECP and confining pressure under the UU condition. When root content is 0.25% in the soil-root composite, GECP is minus and diminishes as the increase of confining pressure. When root content is 0.50%, GECP of HR and VR is minus and the reduction in GECP is small compared with 0.25% root content. But, GECP of CR turns to 0.41 kPa from -1.26 kPa due to confining pressure increases. For the root content of 0.75%, GECP of plant roots gradually increases with an exception that GECP of HR decreases from -0.03 kPa to -2.08 kPa (Table 2).

DISCUSSION

The evaluation mechanism based on GECP

Soil-root composite is a composite system of which plant roots with a high deformation modulus but soil weak. When soil-root composites are destroyed under external load, dislocation occurs between soil and plant roots due to the tremendous difference in deformation modulus. The dislocation is constrained by frictional resistance and interlocking force between soil particles and plant roots. Ulteriorly， root tensile strength and soil compressive strength are effectively combined by the friction of soil-root interface, thus soil shear strength is improved (*Waldron, 1977; Waldron & Dakessian, 1981; Wu et al., 1988; Wu & Watson, 1998; Fan & Su, 2008*).

The reinforcing effect of plant roots on soil is mainly manifested by the addition of cohesion (*Ali & Osman, 2007; Normaniza, Faisal & Barakbah, 2008*), and the internal friction angle is more related to the soil particles structure (*De Baets & Poesen, 2006*). The phenomenon that plant roots affect cohesion rather than internal friction angle of soil-root composites can be explained by that the living plant roots are flexible materials (*Huang et al., 2007*). In addition, root content compared with soil mass is small in soil-root composite, although root content increase, the soil structure is not greatly changed, so the variation of φ value is small (*Chegenizadeh & Nikraz, 2012*).

Compared with the Wu-Waldron model, the evaluation mechanism based on GECP possesses the following merits: (1) different drainage conditions can be considered; (2) different stress-strain characteristics of cohesive soil and sandy soil can be simulated; (3) the effect of drainage condition, root content and root morphology on the reinforced soil can be intuitively mirrored by GECP, which are accurate and reliable. There are some possible discussions, for instance, *Ingold (1983)* showed that the shear strength of soil-root composites is worse under the undrained condition, but our specimens that are not the case.

Effect of root characteristics in reinforced soil

A positive correlation is observed between the shear strength of soil-root composites and root content. When root content is relatively small and increases, the contact area increases gradually due to plant roots can fully contact with soil particles. Plant roots have an effective lateral constraint on soil, the lateral and axial deformation of soil-root composites is reduced, and shear strength is increased compared with un-reinforced soil (*Tan et al., 2019*). As an exception, a stable and obvious reinforcing effect is not produced when root content is 0.25%, due to a less number of plant roots have little effect on the shear deformation. On the contrary, the bonding state of soil is destructed when plant roots are placed in the preparation processes of soil-root composites.

However, relevant studies showed that shear strength of soil-root composites increases with root content increases until the peak value is achieved, and an optimal root content to this peak (*Tan et al., 2019*). When root content continues to increase, excessive plant roots are not effectively connected with soil particles, oppositely, just plant roots mutual contact. Therefore, lateral restraint deformation ability of root system to the soil is no longer strengthened. Inversely, the shear strength of soil-root composites is reduced because of the relative displacement is exacerbated between plant roots. Obviously, the root content is relatively low in this paper, which at the stage of soil reinforcing. The optimal root content is not the focus of this paper, so no further description is granted.

Among the three root distribution types (HR, VR and CR), CR is the best to enhance soil shear strength. With the same root content, soil shear strength is very low under HR, intermediate for VR and highest for CR.

HR doesn't work as a "reinforcement" on soil when root content is less, owing to soil integrity is destroyed and there is less contact area between soil particles and root system. However, when the root system is decussately placed in specimens, root system bears partly horizontal shear force that limits soil lateral deformation, because of the interaction between soil particles and root system. Meanwhile, the rigid modulus of soil-root composites is notably improved, which mainly reflected in the compression modulus of specimens increase, and soil deformation is effectively restrained (*Lewis, 1956*).

Effect of different drainage conditions in reinforced soil

Generally, specimen is consolidated to obtain a different void ratio of specimen, and undrained to keep the void ratio constant (*Mun et al, 2016*). For soil-root composites, the initial porosity of specimens is small under the consolidated condition, the concave-convex structure of root surface is staggered with soil particles. When specimens are loaded, the more energy is required to overcome the interlocking force between soil particles and plant roots. So, the relationship curve between the large principal stress difference and the axial strain of soil-root composites is steeper than unconsolidated condition (*Cazzuffi & Crippa, 2005*).

In the UU triaxial test, soil moisture content and initial porosity are high in specimens. On the one hand, the decrease in electrolyte concentration greatly thickened the water film around soil particles, which increase the space of soil-root interface. Furthermore, the effective surface area of the root-soil interface decreases, so that the interlocking force of soil particles on the root system is reduced. On the other hand, the lubrication effect of water reduces the friction between soil particles and root system, then the soft sliding surface is formed at the interface of soil-root (*Fan & Su, 2008*). In addition, the confining pressure launched on specimens is offset by pore water pressure based on the assumption of the volume of specimens does not vary. The effective stresses of specimens remain stable, so the strength envelope is relatively flat, the value φ is trivial (*Operstein & Frydman, 2000*).

Effect of confining pressure on GECP of root in reinforced soil

In the actual condition, most of *Indigofera amblyantha* roots are concentrated within 0.5 m below the earth surface. When the depth exceeds 0.5 m, the reinforcing effect of plant roots is not obvious due to root content is low (*Waldron & Dakessian, 1982*). Shear strength of specimens is significantly increased under high confining pressure which deviated from the practical application. Therefore, to effectively evaluate the GECP of plant roots in reinforced soil, three levels of confining pressure (50 kPa, 100 kPa and 150 kPa) are established in this paper.

There is a significantly different in reinforcing effect that specimens subjected to different confining pressure (Fig. 5). Under the CD and CU condition, the values of GECP are positive showed that the existence of plant roots in reinforced soil plays a positive role in shear strength. The density of soil-root composites increased as confining pressure augments, resulting in an increase in soil quality of per unit volume. Soil particles gap decreased is more conducive to making plant roots joint with soil, which limits the lateral deformation of specimens. On the other hand, the density increase of specimens aggrandized the number of soil particles contacted with root surface, resulting in a larger contact area and presumably to a higher cohesion of soil-root composites (*De Baets et al., 2008; Abernethy & Rutherfurd, 2010*).

Under the UU condition, GECP of 0.25% root content is minus and diminishes as confining pressure increases. The phenomenon that GECP varies from a negative value to a positive one occurs with root content increases. It can be explained by that fewer plant roots play a role in water transport and the lubrication ability of soil-root interface. Whereas the reinforcing effect of root distribution pattern based on different confining pressure has yet to be studied.

When specimens are subjected to the high confining pressure, soil particles are compacted highly. A less number of plant roots placed in the specimens have little influence on the density of soil particles and the contact area of the soil-root interface. Therefore, the greater in the confining pressure, the smaller the reinforcing effect of plant roots in reinforced soil. However, high confining pressure will make the redundant plant roots fully contact with soil particles when root content gradually increases in specimens. The soil particles at the root-soil interface will move and rearrange until the reinforcing effect of plant roots is effectively exerted. So, the contribution of plant roots to soil strength under high confining pressure is greater than low confining pressure.

CONCLUSION

The evaluation mechanism based on GECP has been applied to evaluate the reinforcing effect of *Indigofera amblyantha* roots on the soil. The results reflect that the main function of plant roots in reinforced soil is to change the soil cohesion. Under the CD and CU conditions, the significant relationships are found between reinforcing effect and root characteristics. The reinforcing effect of root content in reinforced soil followed the sequence of 0.75% > 0.50% > 0.25%, and shear strength of soil-root composites is very low under HR, intermediate for VR and highest for CR. The shear strength of soil-root composites is improved when confining pressure increase, however, the reinforcing effect of plant roots on soil diminishes as confining pressure augment.

Under the UU condition, GECP of 0.25% root content is minus and diminishes as the increase of confining pressure. Some assumptions have been given to explain this phenomenon, but more research is needed to find the cause. Furthermore, the reinforcement mechanism of root distribution pattern with confining pressure change needs to be further studied. In a word, GECP as an indicator to quantitatively evaluate the reinforcing effect of plant roots on soil is intuitionistic and credible, it greatly enriches the mechanism of the plant roots, soil-reinforcement.

ADDITIONAL INFORMATION AND DECLARATION

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Competing Interests

The authors declare that they have no competing interests.

Author Contributions

Hai Xiao, Zhenyao Xia, Qi Liu, and Wennian Xu conceived and designed the experiments; Ping Guo, Qi Liu, Feng Gao, and Lun Zhang performed the experiments; Hai Xiao, Ping Guo, Qi Liu, Lun Zhang, Mingyi Li, and Yueshu Yang analyzed the data; Ping Guo, Feng Gao, Lun Zhang, Mingyi Li, and Yueshu Yang prepared the figures; Ping Guo prepared the tables; Hai Xiao, Zhenyao Xia, Qi Liu, and Wennian Xu drafted the work or revised it critically for important content.

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Figure 1

The relationship of σ_1 and σ_3 of soil-root composite and unreinforced soil.

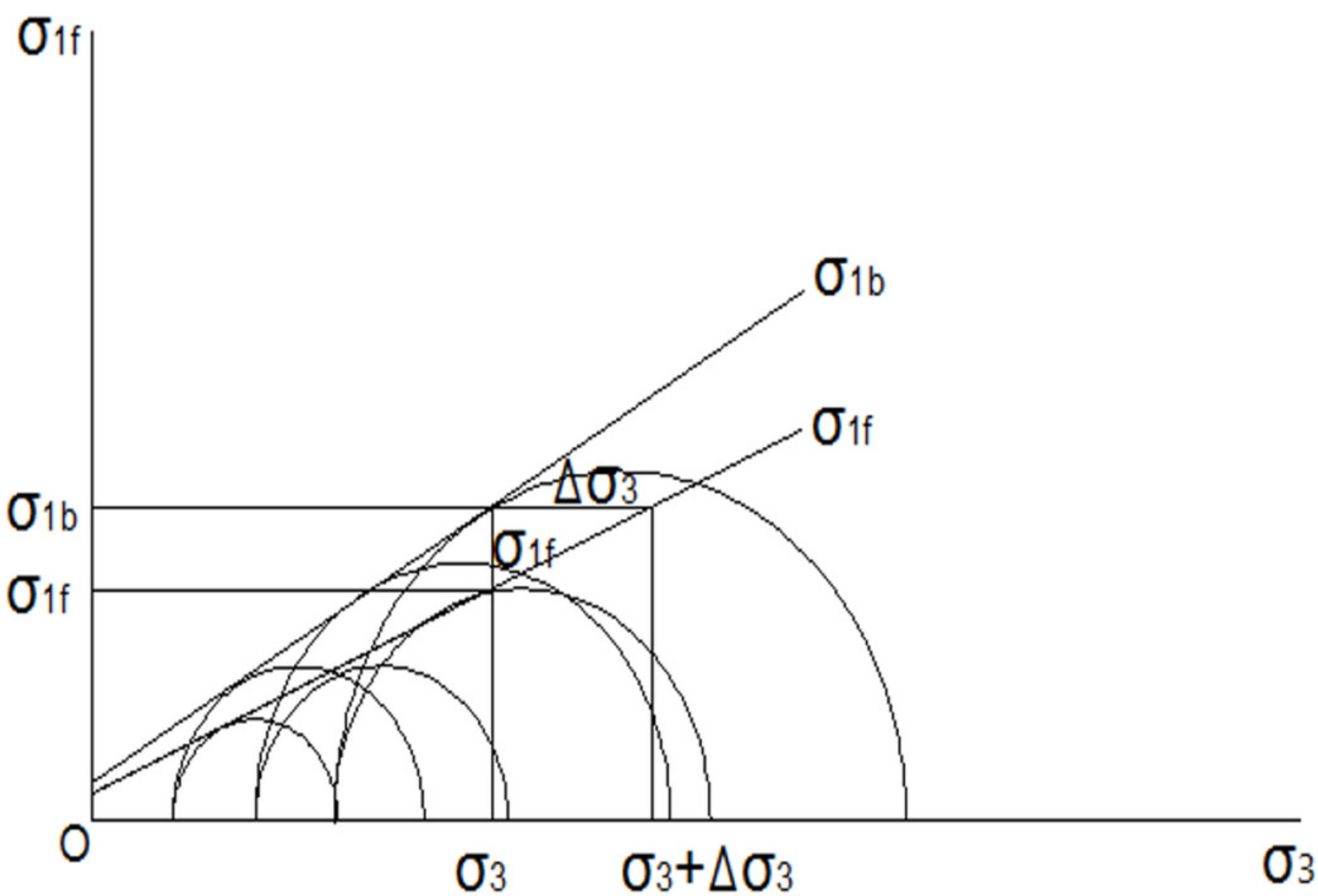

Figure 2

Root distribution patterns in the triaxial test.

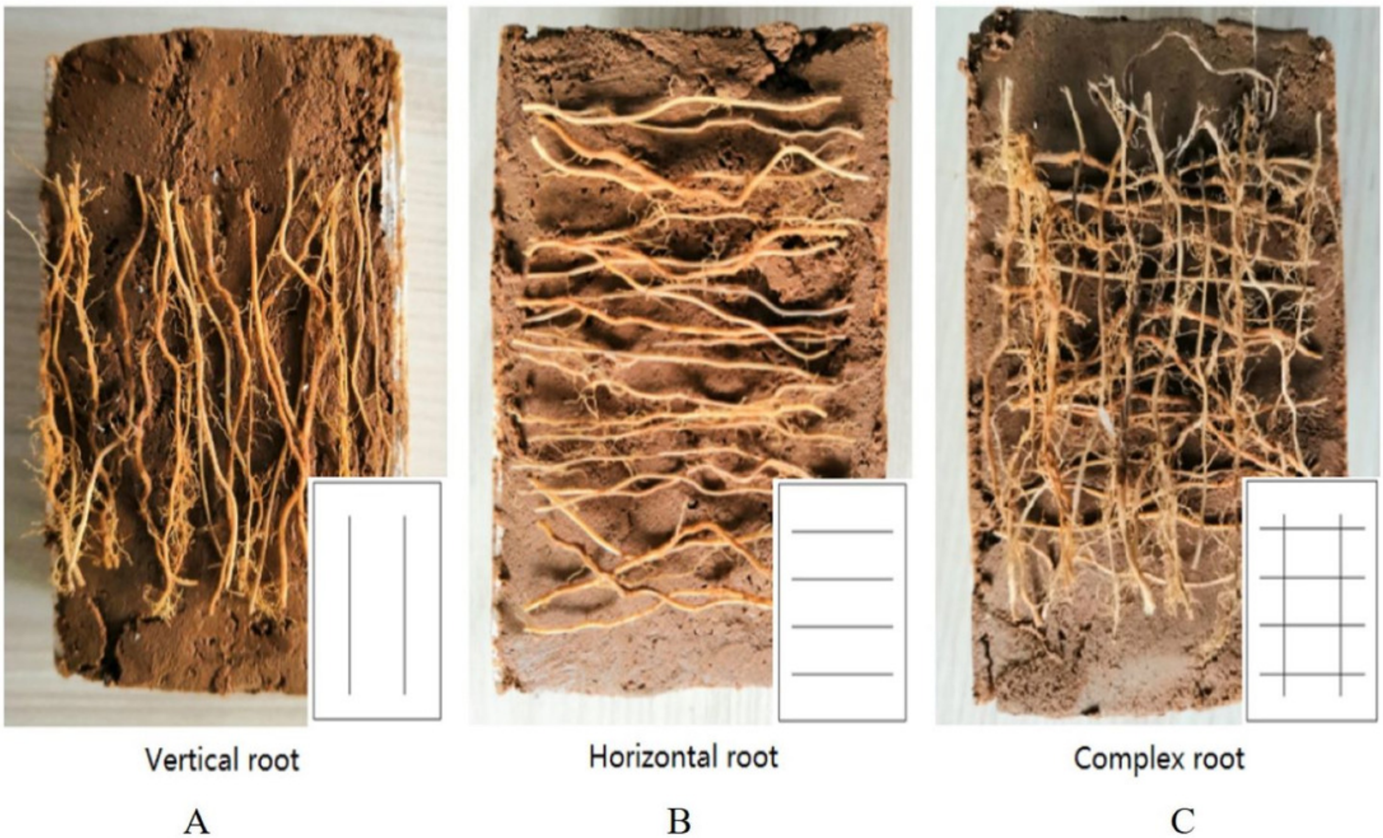

Figure 3

The relationship between generalized equivalent confining pressure of *Indigofera amblyantha* roots in the reinforced soil and root content.

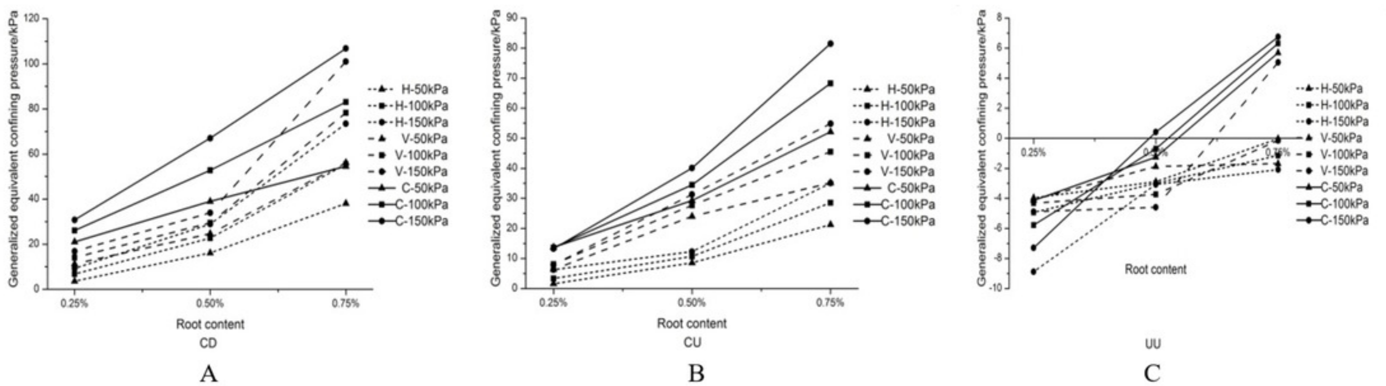

Figure 4

The relationship between generalized equivalent confining pressure of *Indigofera amblyantha* roots in the reinforced soil and drainage condition.

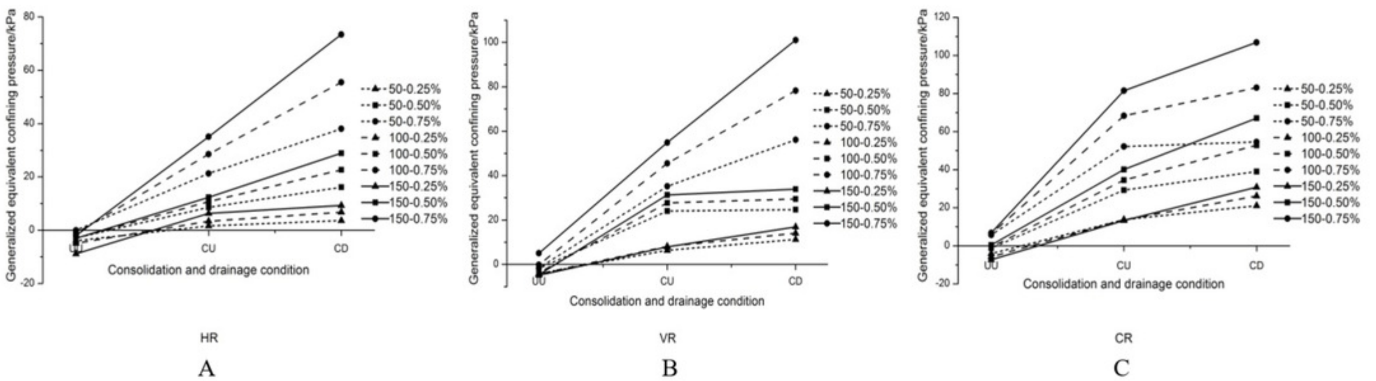

Figure 5

The relationship between generalized equivalent confining pressure of *Indigofera amblyantha* roots in the reinforced soil and confining pressure.

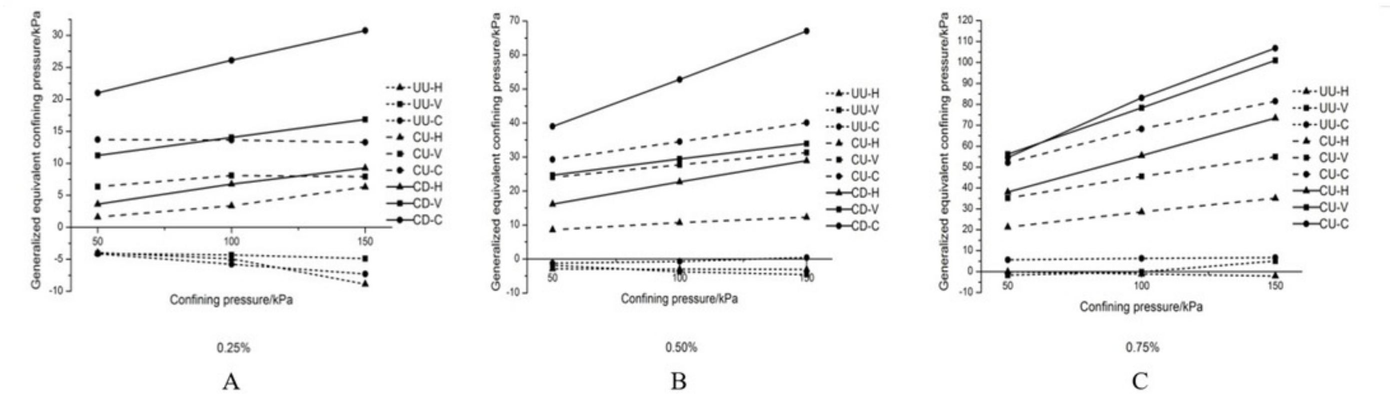

Table 1(on next page)

Shear strength indexes of soil-root composites.

CD denotes the drainage condition of consolidation drained; CU denotes the drainage condition of consolidation undrained; UU denotes the drainage condition of unconsolidation undrained; HR is horizontal root; VR is vertical root; CR is complex root.

Table 1:

Shear strength indexes of soil-root composites.

Control conditions		Experimental method					
		CD		CU		UU	
Distribution pattern	Root content (%)	c/kPa	φ/(°)	c/kPa	φ/(°)	c/kPa	φ/(°)
Un-reinforced soil	0.00	8.24	21.90	6.83	20.10	15.74	11.60
	0.25	7.49	23.40	5.06	20.60	16.71	9.60
HR	0.50	14.10	25.30	11.41	21.10	14.03	11.40
	0.75	19.26	30.00	15.75	23.70	16.43	11.70
	0.25	14.04	23.40	12.56	20.10	15.35	11.20
VR	0.50	21.69	24.40	20.73	22.00	13.27	11.40
	0.75	27.03	31.60	22.94	24.90	11.81	13.50
	0.25	18.98	24.50	16.87	20.00	14.41	11.30
CR	0.50	23.27	28.40	22.47	22.90	14.34	12.00
	0.75	29.00	31.80	28.84	27.30	18.82	12.30

Notes:

CD denotes the drainage condition of consolidation drained; CU denotes the drainage condition of consolidation undrained; UU denotes the drainage condition of unconsolidation undrained; HR is horizontal root; VR is vertical root; CR is complex root.

Table 2(on next page)

Generalized equivalent confining pressure of *Indigofera amblyantha* roots in the reinforced soil.

CD denotes the drainage condition of consolidation drained; CU denotes the drainage condition of consolidation undrained; UU denotes the drainage condition of unconsolidation undrained; HR is horizontal root; VR is vertical root; CR is complex root.

Table 2:

Generalized equivalent confining pressure of *Indigofera amblyantha* roots in the reinforced soil.

Confining pressure (kPa)	Root content (%)	CD			CU			UU		
		HR	VR	CR	HR	VR	CR	HR	VR	CR
50	0.25	3.61	11.23	21.01	1.61	6.35	13.72	-3.97	-4.10	-4.14
	0.50	16.13	24.66	39.01	8.56	24.03	29.26	-2.90	-1.87	-1.26
	0.75	38.07	56.18	54.57	21.26	35.17	52.14	-0.03	-1.68	5.69
100	0.25	6.75	14.06	26.11	3.36	8.10	13.65	-4.93	-4.32	-5.78
	0.50	22.68	29.45	52.80	10.69	27.71	34.50	-2.99	-3.74	-0.70
	0.75	55.50	78.30	83.08	28.55	45.54	68.28	-1.15	-0.13	6.31
150	0.25	9.26	16.87	30.75	6.30	7.92	13.29	-8.89	-4.89	-7.29
	0.50	28.92	33.91	67.05	12.34	31.30	40.10	-3.07	-4.59	0.41
	0.75	73.45	101.03	106.83	35.09	54.89	81.50	-2.08	5.05	6.75

Notes:

CD denotes the drainage condition of consolidation drained; CU denotes the drainage condition of consolidation undrained; UU denotes the drainage condition of unconsolidation undrained; HR is horizontal root; VR is vertical root; CR is complex root.