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

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ABSTRACT

Background: To quantitatively evaluate the contribution of plant roots to soil shear strength, the generalized equivalent confining pressure (GECP), which is the difference in confining pressure between the reinforced and un-reinforced soil specimens at the same shear strength, was proposed and considered in terms of the function of plant roots in soil reinforcement.

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), and unconsolidated undrained (UU)) were used to analyse the influences of different root distribution patterns (horizontal root (HR), vertical root (VR), and complex root (CR)) and root contents (0.25%, 0.50%, and 0.75%) on the shear strength of soil-root composites.

Results: The cohesion (c) values of the soil-root composites varied under different drainage conditions and root contents, while the internal friction angle (φ) values remain basically stable under different drainage conditions. Under the same root content and drainage conditions, the shear strength indexes ranked in order of lower to higher were HR, VR and CR. The GECP of the soil-root composites with a 0.75% root content was 1.5-2.0 times that with a 0.50% root content and more than 5 times that with a 0.25% root content under the CD and CU conditions. The GECP in reinforced soil followed the sequence of CD > CU > UU. The GECP of the plant roots increased as confining pressure increased under CD and CU conditions while showed a complex change to the confining pressure under the UU condition.

Conclusion: It was concluded that the evaluation of plant root reinforcing soil based on GECP can be used to measure effectively the influences of roots on soil under different drainage conditions and root distribution patterns.

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

INTRODUCTION

Plant roots play an important role in improving the overall stability of the superficial slope soil and increasing the safety coefficient of the slope (*Zegeye et al., 2018; Zhou & Wang, 2019*). The plant root system is a complex and dynamic system, for which non-destructive monitoring is difficult, so it is always a challenging aspect to consider in research regarding the mechanism of plant root reinforcing soil.

At present, the evaluation 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, mechanical reinforcement is provided by 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 obvious way in which vegetation enhances slope stability is root reinforcing.

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 analyse the effect of plant

57   roots on slope stability, many in situ and laboratory tests have been carried out on vegetated soil

58   (*Wu & Watson, 1998; Operstein & Frydman, 2000*), and corresponding analytical models for

59   soil-root composites have also been developed (*Waldron, 1977; Waldron & Dakessian, 1981;*

60   *Wu et al., 1988*). For example, a linear equation of root population density and soil shear strength

61   was obtained (*Endo & Tsurnta, 1969*), in which the cohesion strength extending to the sliding

62   layer has a stabilizing effect on shallow slopes, by in situ shear tests (*Gray & Ohashi., 1983;*

63   *Greenway, 1987*).

64   In addition, some mechanistic models like the Wu-Waldron model, the modified Wu-Waldron

65   model, the fiber bundle model, the root bundle model and have been developed to evaluate the

66   additional shear strength provided by plant roots (*Wu, 1976; Waldron, 1977; Wu, McKinell $*

67   *Swanston, 1979; Gray & Sotir, 1998; Pollen & Simon, 2005; Schwarz et al., 2010*). However, as

68   the most classic and representative model, the Wu-Waldron model potentially significantly

69   overestimates the actual cohesion of soil-root composites (*Waldron & Dakessian, 1981;*

70   *Operstein & Frydman, 2000; Pollen & Simon, 2005*), because the Wu-Waldron model or the

71   modified Wu-Waldron model is derived based on the assumption that plant roots are elastic and

72   initially oriented perpendicular to the shear surface and that the friction angle of the soil is

73   unaffected by the plant roots (*Waldron, 1977; Greenway, 1987*). Therefore, a correction factor

74   ranged from 0.34 to 0.50 for roots of herbs and shrubs was proposed by *Schwarz et al. (2010)* to

75   reduce the error of the Wu-Waldron model. The equation of generalized equivalent confining

76   pressure (GECP) is derived based on the limit equilibrium state of reinforced soil and un-

77   reinforced soil (*Huang et al., 2007*), in which the assumptions of root characteristics and root

78   distribution can be ignored. The effect of root distribution or root shear failure angle on soil can

79   be shown by the deviator of the failure principal stresses of reinforced and un-reinforced soil

80   under the same confining pressure. Therefore, we try to introduce this method to assess the

81   additional shear strength provided by plant roots.

82   Decisive factors controlling shallow landslides are the mechanical properties of the sloping

83   soil characteristics (e.g., texture), frequency and duration of the rainfall, and plant species (root

84   morphology) (*Matsushi, Hattanji & Matsukura, 2006; Normaniza, Faisal & Barakbah, 2008*).

85   Rainfall may give rise to shallow landslides because it can increase in soil moisture content so

86   that make the slope in instability stage when other conditions were the same. The effect of plant

87   roots on the shear strength of vegetated soil significantly decreases because of the rainfall

88   (*Normaniza &Barakbah, 2006; Jiang, Dong & Wang, 2009*).

89   Differences in depth, soil moisture content and root characteristics may result in a substantial

90   change in soil shear strength. The effect of plant roots in reinforced soil is understood as an

91   additional confining pressure to the soil, in excess of the traditional equivalent confining pressure.

92   Therefore, the expression of generalized equivalent confining pressure (GECP) was derived to

93   investigate the influence of root contents and root distribution patterns on the shear strength of

94   reinforced soil under different drainage conditions (consolidation drained (CD), consolidation

95   undrained (CU), and unconsolidated undrained (UU)) and was used to analyse the influences of

96   different root distribution patterns (horizontal root (HR), vertical root (VR), and complex root

97 (CR) patterns) and root contents in this research. This research provides new sight to assess the
98 additional shear strength provided by plant roots for the soil-root composite.

MATERIAL AND EXPERIMENTAL METHODS

Experimental materials

101 In this paper, the soil was taken from the cutting slope of the first phase of the urban expressway
102 along the Xiazhou Avenue in Yichang, China. The test soil was collected from 0.3 m below the
103 surface, and the impurities in the soil were removed. The soil was air-dried, crushed and sieved
104 through a 2.0 mm sieve. The soil had a silt loam texture with 24.08% sand (0.05-2.00 mm),
105 55.91% silt (0.002-0.05 mm), and 20.01% clay (<0.002 mm) contents, a 1.38 g cm^{-3} bulk density,
106 a 14.37% natural moisture content, a 2.78% air-dried soil moisture content, and a pH of 6.2.

107 *Indigofera amblyantha*, used widely in slope greening projects, were the roots selected as the
108 reinforcing material. *Indigofera amblyantha* is a perennial deciduous shrub, and its growing
109 period is approximately 6 months; it possesses strong drought resistance and barren resistance.
110 These plants are the most common soil-water conservation plants in tropical and subtropical
111 regions.

112 *Indigofera amblyantha* has a horizontally developed root system, including many branches
113 and fibrous roots (Fig. 1), and the root diameter is mostly concentrated within 1.0-2.5 mm. In
114 this paper, 50 plants of *Indigofera amblyantha* were excavated by the whole excavation method.
115 Normal and straight roots were cut to lengths of 30 mm and 60 mm with scissors. The roots with
116 an average diameter of 1.4-1.6 mm were chosen, of which the average tensile resistance and the
117 average tensile strength were 62.10 N and 35.86 MPa, respectively.

118

Experimental methods

120 The density and moisture content of the soil-root composites were set according to the actual
121 situation of the test soil taken from the cutting slope (bulk density is 1.38 g cm^{-3}, and natural
122 moisture content is 14.37%). The root contents (the ratio of the root mass to soil mass in the
123 specimens) were set to 0.25%, 0.50% and 0.75%.

124 The *Indigofera amblyantha* has a horizontally developed root system, resulting most of the
125 roots are in vertical stage on the slope. To evaluate the effect of root distribution patterns on the
126 shear strength of reinforced soil and ensure the vertical roots are much more than the horizontal
127 roots, the root distribution patterns were categorized into VR, HR and CR in this research (Fig.
128 2A, B, C). The first form (A) is VR with a root length of 60 mm; the second form (B) is HR with
129 the root length is 30 mm; the third form (C) is CR with the ratio of the horizontal to vertical roots
130 is 1:1 in mass (2:1 in number). In this paper, plant roots were organized in the centre of soil-root
131 composites in three forms.

132 As most *Indigofera amblyantha* roots are concentrated within 0.5 m below Earth's surface.
133 When the depth exceeds 0.5 m, the reinforcing effect of plant roots is not obvious because the
134 root content is low (*Waldron & Dakessian, 1982*). Therefore, to effectively evaluate the GECP
135 of plant roots in reinforced soil, three levels of confining pressure (50 kPa, 100 kPa and 150 kPa)
136 are tested in this paper.

137   Soil-root composites were remoulded in a circular loading box of Φ 39.1 mm×80 mm (Fig.
138   2D), which matched with the TSZ-1 strain-controlled triaxial compression apparatus. First, a
139   suitable amount of test soil was weighed and placed in a container that could be sealed, and an
140   appropriate amount of water was sprayed on the soil to reach the moisture content required in
141   this work. Second, the test soil and water were fully mixed, and then the container was sealed for
142   24 h until the test soil was soaked completely. Third, the required amount of soil was taken from
143   the sealed container and placed in the circular loading box mentioned above. Finally, plant roots
144   were buried evenly in the soil, and the method of three-layer compaction was adopted to remould
145   the soil-root composites in the circular loading box according to the standardized methods of soil
146   mechanics test and specimen preparation. In addition, specimens of un-reinforced soil were also
147   prepared, and the preparation processes for the reinforced and un-reinforced samples were
148   consistent except that no roots were present in the un-reinforced specimens.
149   A prepared specimen was put into the pressure room on which 20 kPa of confining pressure
150   was applied. Water entered the specimen base until it flowed from the upper surface, and the
151   constant head was controlled at 1.2 m. The saturated specimens were obtained when the inflow
152   water and the overflow water were equal.
153   Therefore, the un-reinforced and reinforced samples with root content (0.25%, 0.50%, and
154   0.75%), root distribution pattern (HR, VR, and CR), confining pressure (50, 100, and 150 kPa),
155   were performed at the different conditions of shearing rate (0.012 mm min⁻¹ for CD, 0.12 mm
156   min⁻¹ for CU, and 0.9 mm min⁻¹ for UU). The shear strengths of the soil-root composites and un-
157   reinforced soil specimens were measured by triaxial testing with 15% of the axial strain (*Zhang
158   et al., 2010*). All conditions were repeated three times.
159

160   **Generalized equivalent confining pressure (GECP)**
161   The GECP was derived from the traditional equivalent confining pressure. *Gray and Al-Refeai*
162   *(1986)* analysed the failure mechanism of reinforced sandy soil via a triaxial test and derived the
163   expression of traditional equivalent confining pressure under drained conditions (*Moroto, 1992;*
164   *Li et al., 2017):*

165                            $$\Delta\sigma_{3t} = \sigma_3 \frac{\Delta\sigma_{1f}}{\sigma_{1f}}$$ (1)

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

169                            $$\Delta\sigma_{1f} = \sigma_{1fb} - \sigma_{1f}$$ (2)

170   where σ_{1f} is the failure principal stress of un-reinforced soil under a confining pressure of σ_3 and
171   σ_{1fb} is the failure principal stress of reinforced soil under a confining pressure of σ_3.
172   The expression of traditional equivalent confining pressure is proposed for sandy soil under
173   drained conditions, in which cohesion has not been considered (the cohesion of the sandy soil is
174   0). Meanwhile, the function of plant roots in reinforced soil is evaluated, which does not take the
175   effect of the drained condition into account.

176   To avoid these limitations in the traditional equivalent confining pressure, *Huang et al. (2007)*
177   proposed the GECP of cohesive soil and soil-root composites under different drainage conditions,
178   considering that the Mohr-Coulomb strength theory is also obeyed in reinforced soil. GECP is
179   the difference in confining pressure between the reinforced and un-reinforced soil specimens at
180   the same shear strength (Fig. 3). The equation of GECP was derived based on cohesive soil and
181   un-drained condition were comprehensively considered, the traditional equivalent confining
182   pressure of sandy soil can also be realized in the equation of GECP when sandy soil be regarded
183   as a special cohesive soil which with the cohesion is 0. Therefore, to distinguish the expression
184   of traditional equivalent confining pressure, the GECP is expressed as $\Delta\sigma_{3g}$.

185   The limited balance equation of un-reinforced soil is as follows:

$$\sigma_{1f} = \sigma_3 K_p + 2c\sqrt{K_p} \tag{3}$$

187   The limited balance equation of reinforced soil in terms of the difference in confining
188   pressures between the reinforced and un-reinforced soil specimens at the same shear strength is
189   as follows:

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

191   where $\Delta\sigma_{3g}$ represents the generalized equivalent confining pressure; K_p is the passive earth

192   pressure coefficient of cohesive soil, $K_p = tan^2\left(45° + \frac{\varphi}{2}\right)$; and c and φ represent shear strength

193   indexes.
194   Expression of GECP:

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

196   Expression (5) indicates that the GECP of the soil-root composite depends on the deviator of
197   the failure principal stresses of the reinforced and un-reinforced soil specimens, the failure
198   principal stress of the un-reinforced soil and the shear strength indexes of the un-reinforced soil.
199   The expression of the traditional equivalent confining pressure is a special case when the
200   cohesion is 0; then, expression (5) transforms into expression (1). That is, the expression of the
201   traditional equivalent confining pressure proposed is for sandy soil, so sandy soil can be regarded
202   as a cohesive soil when the cohesion is 0.
203
204   **Data analyses**
205   All statistical analyses were performed using by using SPSS with version of 21.0 and Excel
206   with version of 2010. All the data used for further analysing (c, φ and *GECP*) is based on the
207   mean value of the three replications for each condition. Therefore, no statistical test was applied
208   when describe the results of c, φ and *GECP* in this research.
209   **TEST RESULTS**
210   **Shear strength indexes of soil-root composites under different drainage conditions**
211   The shear strength indexes, c and φ, characterized as different trend under different drainage
212   conditions (Table 1). For the un-reinforced soil, the c values were 8.24, 6.83 and 15.74 and the φ
213   values were 21.9°, 20.1° and 11.6°under the CD, CU and UU conditions, respectively. For the

214 reinforced soil, the *c* values varied under different drainage conditions and root contents, while
215 the φ values remain basically stable under different drainage conditions due to the root content,
216 which is different to the results of the un-reinforced soil.
217   Under the CD and CU conditions, the *c* values of the soil-root composites showed obviously
218 increase. The shear strength indexes of the soil-root composites increase the most under the CD
219 condition, with a 251.9% increase in *c* and a 45.2% increase in φ. Under the UU condition, the
220 difference is inconspicuous in the shear strength indexes of the soil-root composites when the
221 root distribution pattern changes. The *c* values present a complicated change trend, which mainly
222 depends on the root distribution pattern and root content. For example, for VR soil-root
223 composites, the *c* decreased from 15.35 kPa to 11.81 kPa as the root content increased from 0.25%
224 to 0.75%. However, for the HR and CR soil-root composites, the *c* decreases and then increases
225 with the increase in root content.
226   Under the same root content and drainage conditions, the *c* values ranked in order of lower to
227 higher were HR, VR and CR, suggesting the CR is the best at enhancing the soil shear strength.
228 **The GECP of *Indigofera amblyantha* roots in the reinforced soil varied by root contents**
229 The values of GECP in the reinforced soil increased with root content (Fig. 4). Under the CD and
230 CU conditions, when the root content is 0.75%, the GECP of the plant roots in the soil-root
231 composites is 1.5-2.0 times that of 0.50% and more than 5 times that of 0.25%. Taking the CD
232 condition as an example, when the soil-root composites are under 150 kPa of confining pressure
233 and the CR content is 0.75%, the GECP of the plant roots in the soil-root composites is 106.83
234 kPa (Table 2). Namely, the shear strength of the soil-root composites under these conditions is
235 equivalent to the strength of un-reinforced soil subjected to a confining pressure of 256.83 kPa.
236 For the UU condition, the GECP of the plant roots was mainly concentrated within the range of -
237 10 kPa to 10 kPa. The GECP of the plant roots increased as the root content increased, largely
238 mirroring the results for the drainage condition. For the CR reinforced soil, the GECP changes
239 from negative to positive as the root content increases, whereas the GECP is always negative
240 under the condition of HR.
241
242 **The GECP of *Indigofera amblyantha* roots in the reinforced soil varied by drainage**
243 **conditions and root distribution patterns**
244 The values of GECP are positive under the CD and CU conditions, while shows from negative to
245 positive under UU condition (Fig. 5). Generally, the values of GECP followed the sequence of
246 CD > CU > UU. The GECP of the plant roots under CU condition increased by 5.48-74.76 when
247 compared with those under UU condition. And the GECP of the plant roots under CD condition
248 increased by 0.63-46.15 when compared with those under CU condition. The effect of the root
249 distribution pattern on the GECP in reinforced soil followed the sequence of CR > VR > HR.
250 Under the CU and CD conditions, the GECP of CR is 1-2 times that of VR and 2-5 times that of
251 HR. The largest GECP of CR is 106.83 kPa, while it is only 21.26 kPa for HR (Table 2).
252
253 **The GECP of *Indigofera amblyantha* roots in the reinforced soil varied by confining**

254 **pressure**

255 The values of GECP increased as confining pressure increased under CD and CU conditions

256 while showed a complex change to the confining pressure under the UU condition (Fig. 6). The

257 GECP of the plant roots was increased when the confining pressure increased from 50 kPa to 150

258 kPa under CD and CU conditions. When the root content is 0.25% in the soil-root composite,

259 GECP is negative and diminishes as the confining pressure increases under the UU condition.

260 When the root content is 0.50%, the GECP of HR and VR is also negative, and the reduction in

261 GECP is small compared with the results with the 0.25% root content. However, the GECP of

262 CR changes to 0.41 kPa from -1.26 kPa due to the increase in confining pressure. For the root

263 content of 0.75%, the GECP of the plant roots gradually increases, with the exception that the

264 GECP of HR decreases from -0.03 kPa to -2.08 kPa (Table 2).

265 ## DISCUSSION

266 **The evaluation mechanism based on the GECP**

267 The soil-root composite is a composite system in which the plant roots have a high deformation

268 modulus but the soil is weak. When soil-root composites are destroyed under an external load,

269 dislocation occurs between soil and plant roots due to the tremendous difference in their

270 deformation moduli. The dislocation is constrained by the frictional resistance and interlocking

271 force between the soil particles and plant roots. Additionally, the root tensile strength and soil

272 compressive strength are effectively equilibrated by the friction of the soil-root interface; thus,

273 soil shear strength is improved (*Waldron, 1977; Waldron & Dakessian, 1981; Wu et al., 1988;*

274 *Wu & Watson, 1998; Fan & Su, 2008*).

275 The reinforcing effect of plant roots on soil is mainly manifested by the addition of cohesion

276 (*Ali & Osman, 2007; Normaniza, Faisal & Barakbah, 2008*), and the internal friction angle is

277 mainly related to the soil particle structure (*De Baets & Poesen, 2006*). The phenomenon that

278 plant roots affect the cohesion rather than the internal friction angle of the soil-root composites

279 can be explained by the fact that living plant roots are flexible (*Huang et al., 2007*). In addition,

280 the root content to soil mass ratio is small in the soil-root composite, although as the root content

281 increases, the soil structure does not greatly change, so the variation in the φ value is small

282 (*Chegenizadeh & Nikraz, 2012*).

283 Compared with the Wu-Waldron model, the evaluation mechanism based on the GECP

284 possesses the following merits: (1) different drainage conditions can be considered; (2) different

285 stress-strain characteristics of the cohesive soil and sandy soil can be simulated; (3) the effect of

286 drainage condition, root content and root morphology on the reinforced soil can be intuitively

287 mirrored by the GECP, accurately and reliably. There are some possible points to discuss: for

288 instance, *Ingold (1983)* showed that the shear strength of soil-root composites is worse under

289 undrained conditions than under other conditions, but the results from our specimens do not

290 agree.

291

292 **Effect of the root characteristics in the reinforced soil**

293 The c values of the soil-root composites showed obviously increase under the CD and CU

294 conditions, while it presents a complicated change trend under UU condition (Table 1). The
295 contact area increases gradually with the increase of the root content because the plant roots can
296 be fully in contact with the soil particles. Plant roots provide an effective lateral constraint on
297 soil: the lateral and axial deformation of soil-root composites is reduced and the shear strength is
298 increased compared with the results of un-reinforced soil (*Tan et al., 2019*). As an exception, the
299 stable reinforcing effect is not clearly produced when the root content is 0.25% because the low
300 plant root content has little effect on the shear deformation. In contrast, the bonding state of the
301 soil is destroyed when plant roots are placed in the preparation of the soil-root composites.
302 However, relevant studies have shown that the shear strength of soil-root composites increases
303 with root content until a peak value is achieved, and this peak corresponds to an optimal root
304 content (*Tan et al., 2019*). When the root content continues to increase, the plant roots are not
305 effectively connected with the soil particles, and plant roots come into contact. Therefore, the
306 lateral restraint of the root system in the soil is no longer strengthened. With root contents lower
307 than the optimal root content, the shear strength of the soil-root composites is reduced because
308 the relative displacement is exacerbated between plant roots. Clearly, the root content is
309 relatively low in this paper and represents the stage of soil reinforcing. The optimal root content
310 is not the focus of this paper, so no further discussion is provided on this topic.
311 Among the three root distribution types (HR, VR and CR), CR is the best at enhancing the
312 soil shear strength (Table 2).HR does not effectively reinforce soil when the root content is low
313 because the soil integrity is destroyed and there is a smaller contact area between soil particles
314 and the root system. However, when the root system is decussately placed in specimens, the root
315 system bears some of the horizontal shear force and limits soil lateral deformation because of the
316 interaction between the soil particles and the root system. Meanwhile, the rigid modulus of the
317 soil-root composites is notably improved, which is mainly reflected in the increase in the
318 compression modulus of the specimens, and the soil deformation is effectively restrained (*Lewis,*
319 *1956*).
320
321 **Effect of the different drainage conditions in the reinforced soil**
322 Generally, specimens are consolidated to obtain different void ratios and left undrained to keep
323 the void ratio constant (*Mun et al, 2016*). For soil-root composites, the initial porosity of
324 specimens is small under consolidated conditions, and the concave-convex structure of the root
325 surface is in contact with some soil particles. When specimens are loaded, more energy is
326 required to overcome the interlocking force between the soil particles and plant roots. Therefore,
327 the curve describing the relationship between the large principal stress difference and the axial
328 strain in the soil-root composites is steeper than that for the unconsolidated specimens (*Cazzuffi*
329 *& Crippa, 2005*).
330 In the UU triaxial test, the soil moisture content and initial porosity are high in the specimens.
331 On the one hand, the decrease in electrolyte concentration greatly thickened the water film
332 around the soil particles, which increased the space of the soil-root interface. Furthermore, the
333 effective surface area of the root-soil interface decreases so that the interlocking force of the soil

334   particles on the root system is reduced. On the other hand, the lubrication effect of water reduces
335   the friction between soil particles and the root system, and then a soft sliding surface is formed at
336   the soil-root interface (*Fan & Su, 2008*). In addition, the confining pressure applied to the
337   specimens is offset by the pore water pressure based on the assumption that the volume of the
338   specimens does not vary. The effective stresses of the specimens remain stable, so the strength
339   envelope is relatively flat, therefore, the value of φ is not obviously changed (*Operstein &*
340   *Frydman, 2000*).

341

342   **Effect of the different confining pressure in the reinforced soil**
343   The values of GECP in the reinforced soil increased with root content (Fig. 4). The density of the
344   soil-root composites increased as the confining pressure increased, resulting in an increase in the
345   soil quality per unit volume and a reduce in the soil particle gap. And the plant roots could
346   interlock with soil particles more tightness because of the reducing in the soil particle gap, which
347   limits the lateral deformation of soil. On the other hand, an increase in the specimen density
348   increases the number of soil particles in contact with the root surfaces, resulting in a larger
349   contact area and presumably a higher cohesion in soil-root composites (*De Baets et al., 2008;*
350   *Abernethy & Rutherfurd, 2010*).
351   The values of GECP are positive under the CD and CU conditions, while shows from negative
352   to positive under UU condition (Fig. 5). The phenomenon that the GECP varies from a negative
353   value to a positive value occurs as the root content increases (Fig. 4 and Fig. 5). This
354   phenomenon can be explained by the fact that fewer plant roots enhance the water transport and
355   the lubrication of the soil-root interfaces. The soil shear strength is mainly borne by soil skeleton,
356   which is formed by the free arranging and binding of soil particles, and the biting force and
357   bonding force between soil particles are sensitive to water when the root content is low. However
358   large porosity exists between the interfaces of soil-root, high confining pressure accelerates soil
359   particles gap is filled and the organic calcium of soil particles is dissolved, and the deformation
360   resistance of soil skeleton is reduced (*Pierret et al. 2007*). Thus, fewer plant roots enhance the
361   water transport and the lubrication of the soil-root interfaces. Inversely, high root content can
362   limit soil lateral deformation and effectively reduce soil compression deformation, which is
363   conducive to the dissipation of excess pore water pressure, which delayed change of pore water
364   pressure and increased soil effective stress. However, the reinforcing effect of root distribution
365   patterns based on different confining pressures has yet to be studied.
366   The GECP of the plant roots decreased and increased as confining pressure increased under
367   smaller and higher root contents, respectively (Fig. 6). When specimens are subjected to high
368   confining pressures, the soil particles become highly compacted. A smaller number of plant roots
369   placed in the specimens has little influence on the density of the soil particles and the soil-root
370   contact area. Therefore, the greater the confining pressure is, the smaller the reinforcing effect of
371   plant roots in reinforced soil. However, for higher root contents, a high confining pressure will
372   make the redundant plant roots fully contact the soil particles in the specimens. The soil particles
373   at the root-soil interface will rearrange until the reinforcing effect of the plant roots is effectively

374   exerted. Therefore, the contribution of plant roots to soil strength under a high confining pressure
375   is greater than that under a low confining pressure.

376 **CONCLUSION**

377   An evaluation based on the GECP is applied to assess the reinforcing effect of *Indigofera*
378   *amblyantha* roots on soil. The results reflect that the main function of plant roots in reinforced
379   soil is to change the soil cohesion but not to change the internal friction angle under different
380   drainage conditions. The c values of the soil-root composites showed obviously increase under
381   the CD and CU conditions, while it presents a complicated change trend under UU condition.
382   Under the CD and CU conditions, the c values of the soil-root composites showed obviously
383   increase. The reinforcing effect of the root content in reinforced soil followed the sequence of
384   0.75% > 0.50% > 0.25%, and the *c* values ranked in order of lower to higher were HR, VR and
385   CR.

386   The values of GECP in the reinforced soil increased with root content, and it is positive under
387   the CD and CU conditions, while shows from negative to positive under UU condition with an
388   sequence of CD > CU > UU. The values of GECP increased as confining pressure increased
389   under CD and CU conditions while showed a complex change to the confining pressure under
390   the UU condition. Therefore, the GECP can be used as an intuitive and credible indicator to
391   quantitatively evaluate the reinforcing effect of plant roots on soil and helps to explain the soil
392   reinforcement mechanism of plant roots.

393   The results in this research are based on experiments on one soil type with the *Indigofera*
394   *amblyantha* root. However, the soil characteristics (e.g., texture) and the root of different plant
395   species have great influence on the shear strength of reinforced soil, which of course affect the
396   influence of root contents on the shear strength of reinforced soil. Therefore, more researches
397   under different soil characteristics with different root should be investigated in the future to
398   verify the results obtained in this research.

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407

408   **Competing Interests**
409   The authors declare that they have no competing interests.

410

411   **Author Contributions**
412   Hai Xiao, Zhenyao Xia, Qi Liu, and Wennian Xu conceived and designed the experiments; Ping
413   Guo, Qi Liu, Feng Gao, and Lun Zhang performed the experiments; Hai Xiao, Ping Guo, Qi Liu,

414 Lun Zhang, Mingyi Li, and Yueshu Yang analyzed the data; Ping Guo, Feng Gao, Lun Zhang,
415 Mingyi Li, and Yueshu Yang prepared the figures; Ping Guo prepared the tables; Hai Xiao,
416 Zhenyao Xia, Qi Liu, and Wennian Xu drafted the work or revised it critically for important
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Figure 1

The root distribution of the *Indigofera amblyantha.*

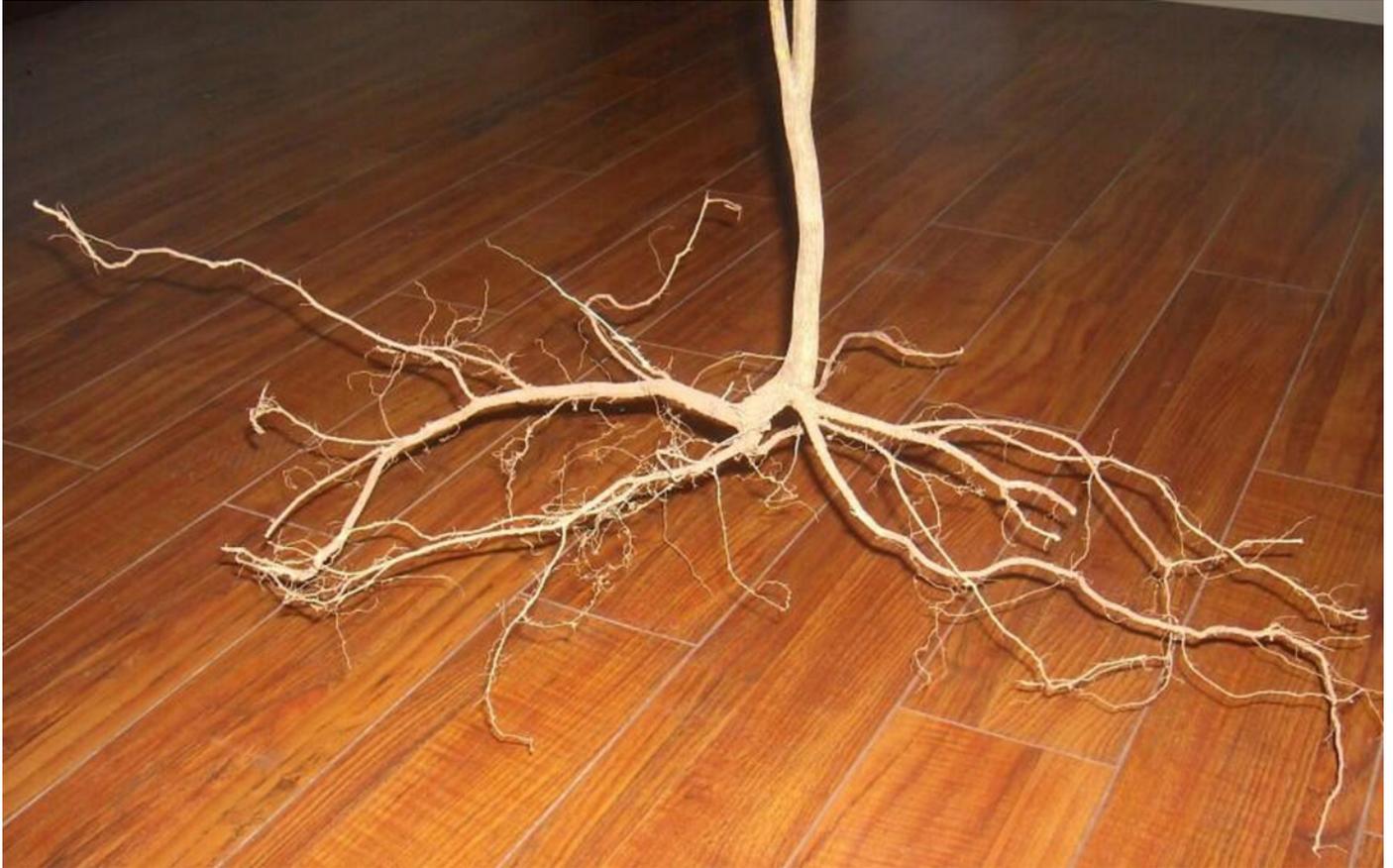



Figure 2

Root distribution patterns in the triaxial test.

Vertical root
(A)

Horizontal root
(B)

Complex root
(C)

Soil samples
(D)

Figure 3

The relationship between σ_1 and σ_3 in the soil-root composite and un-reinforced soil.

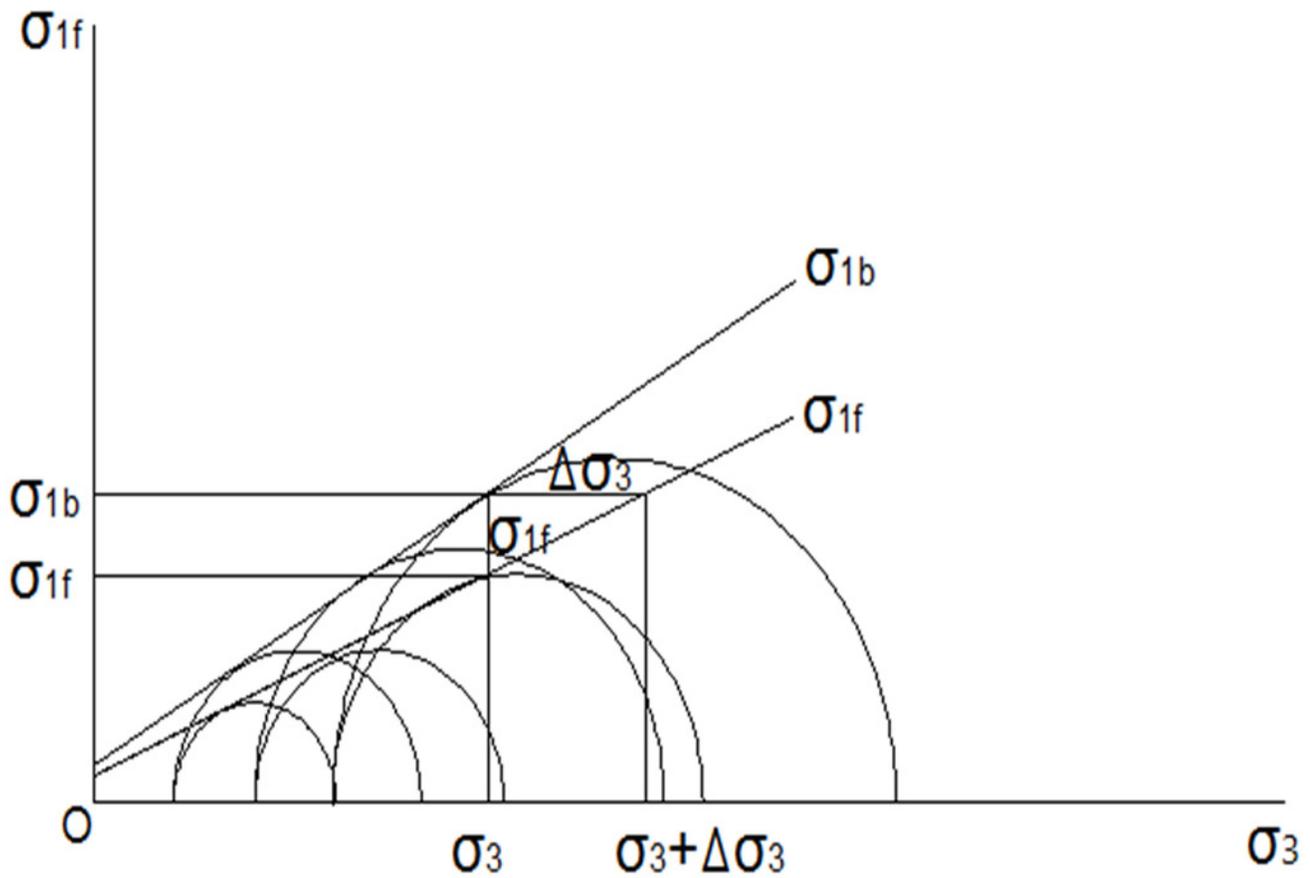



Figure 4

The generalized equivalent confining pressure of *Indigofera amblyantha* roots in the reinforced soil varied by root content s. (A) Consolidation drained (CD). (B) Consolidation undrained (CU). (C) Unconsolidated undrained (UU).

In the legend, H, V and C denote the root distribution patterns are vertical root, horizontal root and complex root, respectively. 50, 100 and 150 kPa denote the confining pressures are 50, 100 and 150 kPa, respectively.

Legend:
- H-50 kPa
- H-100 kPa
- H-150 kPa
- V-50 kPa
- V-100 kPa
- V-150 kPa
- C-50 kPa
- C-100 kPa
- C-150 kPa

Root content
CD
(A)

Root content
CU
(B)

Root content
UU
(C)

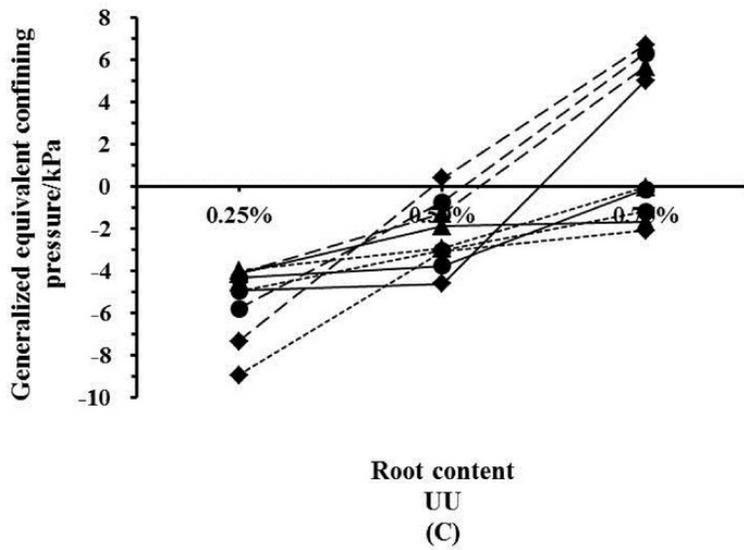
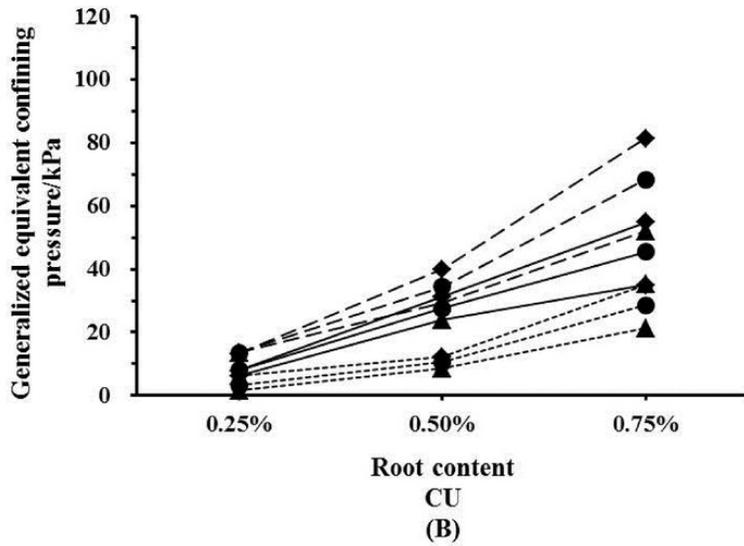
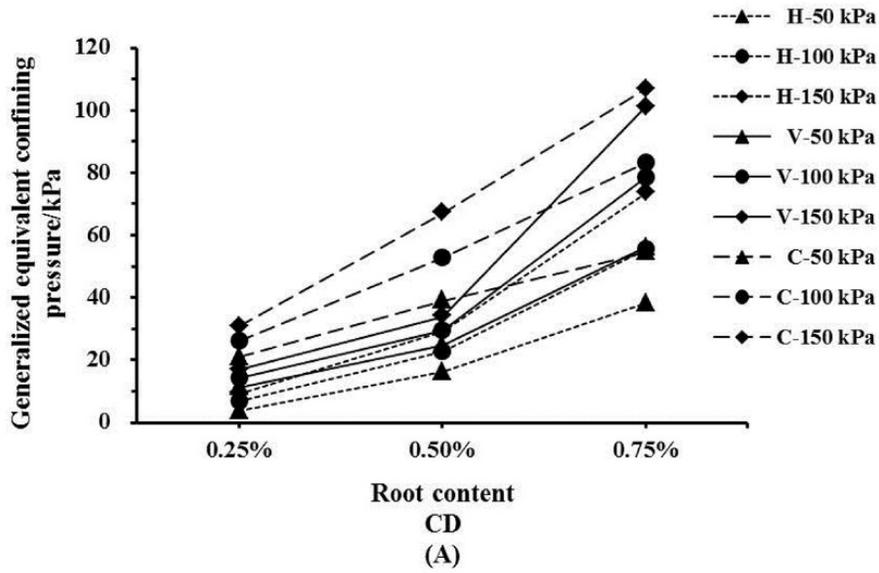



Figure 5

The generalized equivalent confining pressure of *Indigofera amblyantha* roots in the reinforced varied by drainage conditions. (A) Horizontal root (HR). (B) Vertical root (VR). (C) Complex root (CR).

In the legend, 50, 100 and 150 kPa denote the confining pressures are 50, 100 and 150 kPa, respectively. 0.25%, 0.50% and 0.75% denote the root contents are 0.25%, 0.50% and 0.75%, respectively.

Drainage condition
HR
(A)

Drainage condition
VR
(B)

Drainage condition
CR
(C)

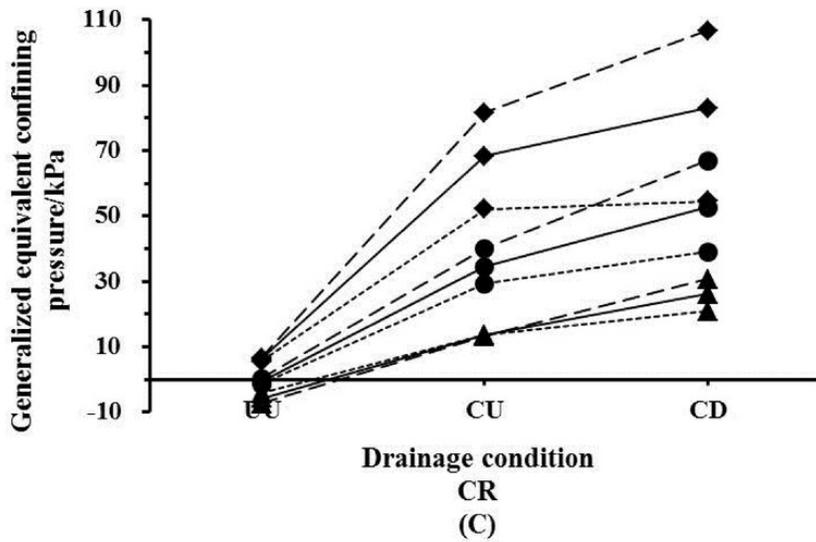
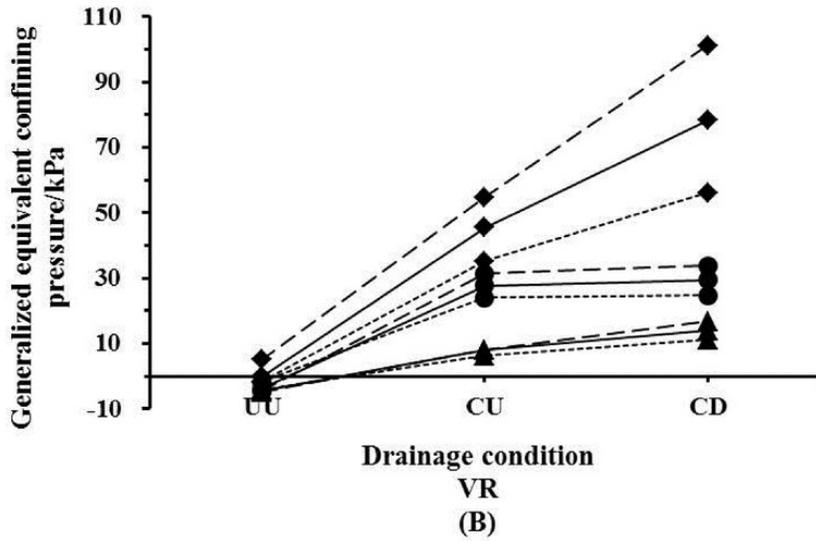
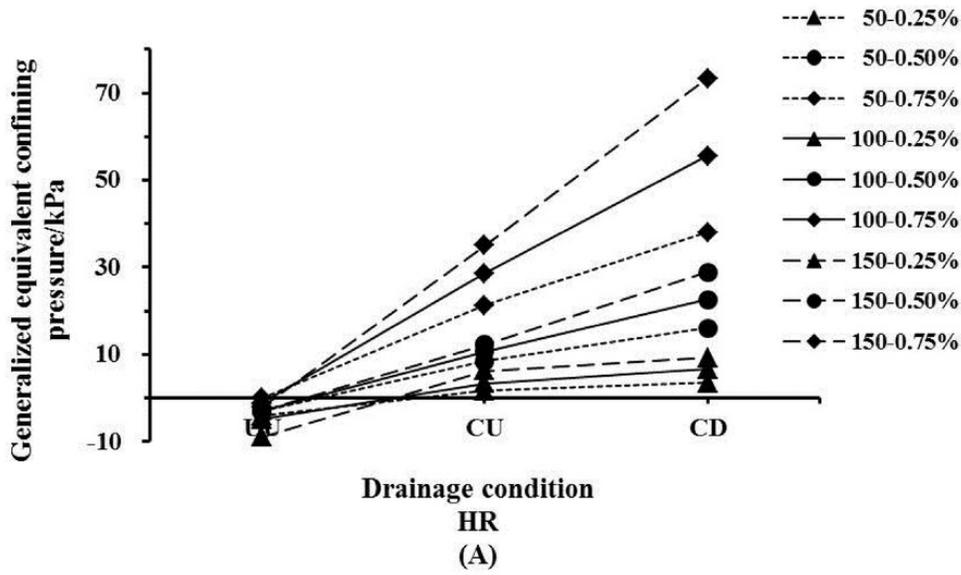



Figure 6

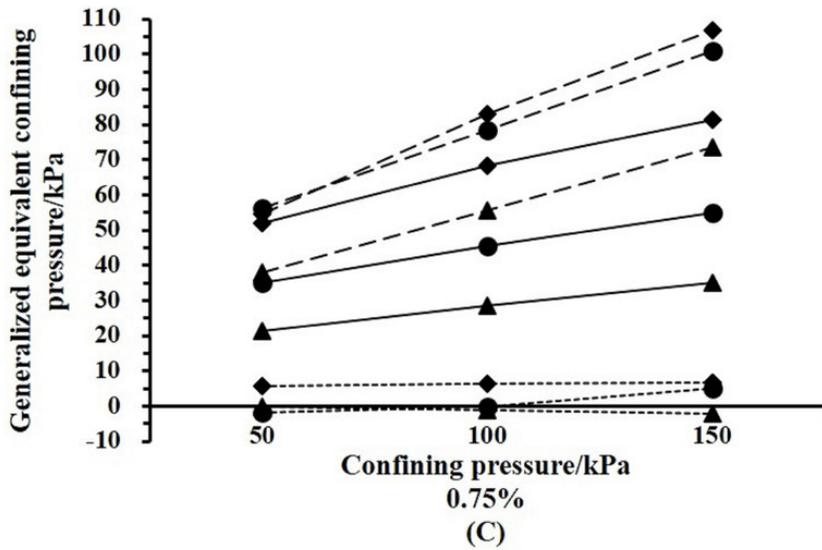
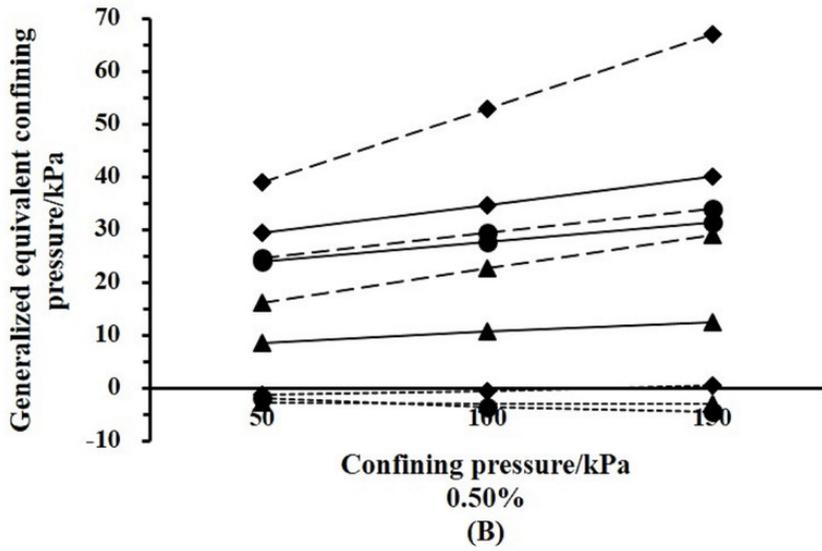
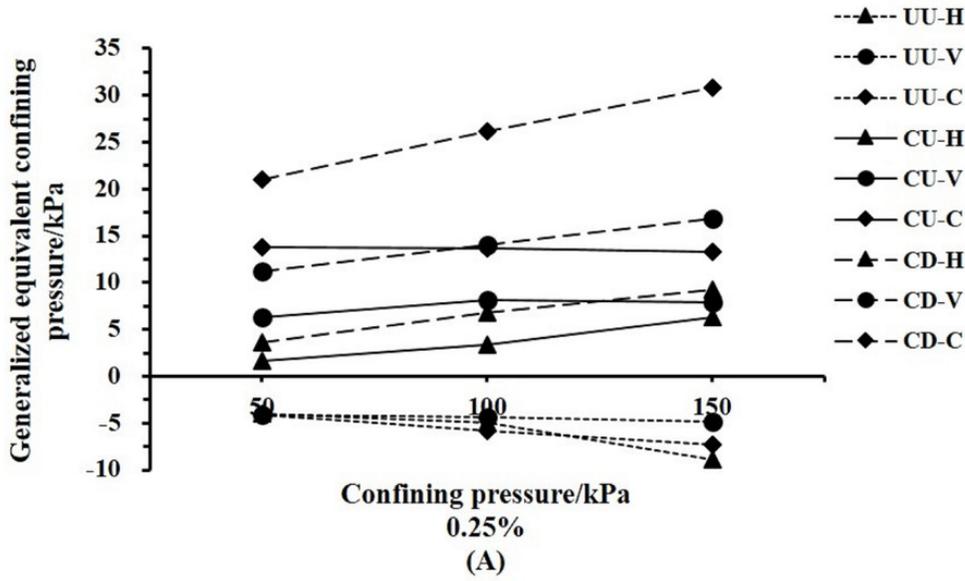
The generalized equivalent confining pressure of *Indigofera amblyantha* roots in the reinforced soil varied by confining pressure. (A) The root content is 0.25%. (B) The root content is 0.50%. (C) The root content is 0.75%.

In the legend, UU, CU and CD denote the drainage conditions are unconsolidated undrained, consolidation undrained and consolidation drained, respectively. H, V and C denote the root distribution patterns are vertical root, horizontal root and complex root, respectively.

Legend:
--▲--- UU-H
--●-- UU-V
--◆-- UU-C
——▲—— CU-H
——●—— CU-V
——◆—— CU-C
— ▲ — CD-H
— ● — CD-V
— ◆ — CD-C

(A) Confining pressure/kPa 0.25%

(B) Confining pressure/kPa 0.50%

(C) Confining pressure/kPa 0.75%

Shear strength indexes of soil-root composites.

Notes: CD denotes the consolidation drained condition; CU denotes the consolidation undrained condition; UU denotes the unconsolidated undrained condition; HR is horizontal root; VR is vertical root; CR is complex root.

1 **Table 1:**

2 **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

3 **Notes:** CD denotes the consolidation drained condition; CU denotes the consolidation undrained condition;

4 UU denotes the unconsolidated undrained condition; HR is horizontal root; VR is vertical root; CR is complex

5 root.

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

Notes: CD denotes the consolidation drained condition; CU denotes the consolidation undrained condition; UU denotes the unconsolidated undrained condition; HR is horizontal root; VR is vertical root; CR is complex root.

1   **Table 2:**

2   **Generalized equivalent confining pressure (GECP) of *Indigofera amblyantha* roots in the**

3   **reinforced soil.**

Confining pressure (kPa)	Root content (%)	CD			CU			UU		
		HR	VR	CR	HR	VR	CR	HR	VR	CR
	0.25	3.61	11.23	21.01	1.61	6.35	13.72	-3.97	-4.10	-4.14
50	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
	0.25	6.75	14.06	26.11	3.36	8.10	13.65	-4.93	-4.32	-5.78
100	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
	0.25	9.26	16.87	30.75	6.30	7.92	13.29	-8.89	-4.89	-7.29
150	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

4   **Notes:** CD denotes the consolidation drained condition; CU denotes the consolidation undrained condition;

5   UU denotes the unconsolidated undrained condition; HR is horizontal root; VR is vertical root; CR is complex

6   root.