**In-situ horizontal extrusion test of herbaceous root–soil with different root types**

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In-situ horizontal extrusion test of herbaceous root–soil with different root types

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Abstract:

The influence of different types of roots on the soil is complex and still remains unclear. Four in-situ extrusion tests were conducted on two types of root systems, namely fibrous and tap root system, for three plants (i.e. Eleusine indica, Potentilla anserine and Artemisia argyi), according to the classification in *Botany*, and the thrust–displacement curves and failure patterns of different samples were analysed by comparison to fill the aforementioned gap. Results reveal that the roots can reduce the characteristics of soil brittleness and enhance its capability to resist large deformation, and different root types contribute different effects on the strain-hardening behaviour of the root–soil mass. The contribution of the fibrous root system on strength is limited, whilst the tap root system substantially enhances strength and stiffness. Results of failure patterns show that fibrous and tap root systems affect soil solidification and surface cracking reduction. However, the effect of the tap root system depends on the composition of lateral and tap roots: long and rich lateral roots are effective for resisting the creation of cracks, but thick tap roots with few and thin lateral roots may lead to several surface cracks.

Keywords:

Root types; Fibrous root; Tap root; In-situ horizontal extrusion test; Root-soil
1. Introduction

Mountainous regions are often characterised with sensitive and changeable climate and serious soil erosion and related geohazards. These characteristics seriously threaten the lives and properties of people as well as the safety of engineering construction and restrict the exploitation of resources and economic development in mountainous areas. Reducing soil erosion and relieving mountainous geohazards are crucial to ensure the sustainable development of mountainous regions.

The roots of plants have positive effects on soil stabilisation of the slope protection (Waldron, 1977; Waldron and Dakessian, 1981; Coutts, 1983, 1987; Abe and Ziemen, 1991; Coutts et al., 1999; Watson et al., 1999; Fredlund and Hung, 2001; Indraratna et al. 2006; Cui and Lin, 2013; Ng CWW et al., 2013, 2016). Root systems have the mechanical function of ‘reinforcement’ and ‘anchoring’ to the soil, which is mainly attributed to the sliding friction of the contact surface between roots and soil as well as the static friction of roots to resist the sliding tendency of soil (Waldron, 1977; Waldron and Dakessian, 1981; Wu et al., 1988; Stokes et al., 2009; Abdi et al., 2010; NG CWW, 2017).

The mechanical effects of roots to soil have been experimentally studied on many instances, such as the in-situ direct shear test or some other ways with fixed shear plane same as the direct shear (Endo and Tsutura, 1969; Ziemer, 1978; O’Loughlin, 1981; Wu et al., 1988; Zhou et al., 1997, 2000). Campbell and Hawkins (2003) and Pallewattha et al. (2019) also conducted indoor direct shear tests of root–soil.
Some researchers investigated the effect of root modulus to the mechanical characteristics of soil by fibre samples (Gray and Ohashi, 1983; Mickovski, 2009). Others analysed the influence of root systems on the mechanical properties of soil by testing the effect of root parameters on its tensile strength (Nilaweera et al., 1999; Zhou et al., 2000; Comino and Marengo, 2010).

The above-mentioned tests aim to analyse the influence of root systems on soil properties qualitatively or quantitatively with one or some typical plants (i.e. Persian ironwood (Abdi et al., 2010); paper birch and lodgepole pine (Campbell and Hawkins, 2003); Rosa canina, Cotoneaster dammeri and Juniperus horizontalis (Comino and Marengo, 2010); Caragana korshinskii, Hippophae rhamnoides and Hedysarum fruticosum (Ge et al., 2014); Zygophyllum xanthoxylon and Caragana korshinskii (Yu et al. 2013); Yunnan Pine (Zhou et al. 2000)). However, few scholars have studied the effect of different root types on the shear behaviour of soil based on the botanical classification of roots. Zhang et al. (2010) suggested that the direct shear has the largest problem considering failure plane despite its easy operation and its capability to quantify the influence of roots in some aspects. Different from the direct shear, the in-situ horizontal extrusion test, which does not preset the shear plane in advance, has been rarely performed despite its consistency with the actual failure process.

Given the paucity of existing research, the current study initially conducted four in-situ horizontal extrusion tests on two types of root systems (the fibrous root system i.e. Eleusine indica (L.) Gaertn and tap root system i.e. Potentilla anserine L., Artemisia
argyi Levl. et Van) based on the botanical classification. Then, this study investigated
the shear failure properties of root–soil by comparing the thrust–displacement curves
and failure patterns of different samples. Finally, the different reinforcement effects and
mechanisms of two types of root systems on the soil were comprehensively detailed.

2. Methodology

2.1 Two types of root systems

The Botany (Jin, 2006) indicates that the radicle initially breaks through the seed
coat and forms the tap root during seed germination of terrestrial plants. The lateral
roots of different levels will develop when the tap root grows to a certain length. These
roots developed in specific parts of the plant are defined as fixed roots, whilst those
grown from stems, leaves, old roots and hypocotyls are called adventitious roots.
Adventitious roots can also produce lateral roots.

Consequently, the root system was divided into tap and fibrous root systems
respectively based on the composition of fixed and adventitious roots (Fig. 1). Tap root
systems mainly comprise fixed roots, in which the taproot is developed deep into the
soil, and lateral roots at all levels are gradually short. The plants of tap root system
mostly comprise dicotyledonous plants, such as cotton and jute. Fibrous root system
mostly comprises adventitious roots and their lateral roots, which have the similar
diameters and lengths. Distinct from the tap root system, the fibrous root system does
not have taproot. Most monocotyledonous plants, such as wheat and maize, belong to
this group. Therefore, three plants belonging to the two above-mentioned types of root
system (the fibrous root system i.e. Eleusine indica (L.) Gaertn and tap root system i.e.
Potentilla anserine L., Artemisia argyi Levl. et Van) are selected to design the in-situ
shear test.
2.2 Study site and sample

These experiments were conducted in Reshui River, Xide County, Sichuan Province, China (2050–2590 m altitude, 28°6′–28°9′ N, 102°16′–102°18′ E). Four test sites, including site I, site II in the Laowa gully and sites III and IV in the Fencha gully, were selected on the basis of the varieties and distribution of the vegetation (Fig. 2). The two gullies, which are approximately 5 km apart with similar geological conditions, mainly comprise middle mountain landform with large topographic slope. Abundant and strong rainfall in summer is also observed in this region. The surface layer of the Quaternary, which comprises clay silt, clay and sandy gravel layers, is mostly alluvium and diluvium. Amongst the four test sites, sites I, II, III and IV are respectively for Eleusine indica root soil, Potentilla anserine root soil, Artemisia argyi root soil and unplanted soil.
Eleusine indica is the annual herb, whilst Potentilla anserine and Artemisia argyi are all perennial herbs. The roots of the used Eleusine indica are reticulated and vertically distributed in the range of 12 cm based on measurements, with a mean diameter of 0.5–1 mm (Fig. 3(a)). Artemisia argyi and Potentilla anserine have differences in characteristics despite belonging to tap root system herbs. The total root number of Potentilla anserine is small, including a distinct taproot and a few lateral roots. The length of the taproot is approximately 5–7 cm with an average diameter of approximately 6 mm, and lateral roots are short with an average diameter of approximately 0.2 mm (Fig. 3(b)). However, Artemisia argyi has more roots than Potentilla anserine, especially for the lateral roots. Different from Potentilla anserine, the taproot of the Artemisia argyi has an average diameter of 5 mm, and its longitudinal
extension is approximately 18–20 cm. The lateral roots mostly dip at 30°, and their
diameters at all levels range from 0.2 mm to 2 mm (Fig. 3(c)).

Fig. 3 Herbaceous plants and roots used in the experiment: (a) Eleusine indica; (b) Potentilla anserine; (c) Artemisia argyi

As required by the Geological Engineering Handbook (2018), the height of the sample should be five times of the maximum particle diameter. The width of the sample should be three or four times of the height and approximately equal to the length. The sample size of 0.9 m × 0.9 m × 0.3 m (length × width × height) was set on the basis of the soil conditions, and the excavation range of the test pit was 1.5 m × 1.28 m × 0.3 m (Fig. 4). The specimens were excavated into three sides facing the air. Four samples completed are shown in Fig. 5.

Fig. 4 Schematic of sample size / mm
Fig. 5 Samples for horizontal extrusion test: (a) Unplanted soil sample, (b) Eleusine indica sample, (c) Potentilla anserine sample, (d) Artemisia argyi sample

The moisture content, density and particle composition of the soil in the four samples were obtained 15 cm below the surface during the excavation. Three parallel tests were conducted to study the moisture content and density in each sample and guarantee the accuracy. Data are summarised as shown in Table 1.

Table 1 Basic physical parameter of four samples

<table>
<thead>
<tr>
<th>Valley</th>
<th>Site</th>
<th>Sample</th>
<th>Moisture content (%)</th>
<th>Density g/cm³</th>
<th>d₆₀</th>
<th>d₅₀</th>
<th>d₃₀</th>
<th>d₁₀</th>
<th>Cu</th>
<th>Cc</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>I</td>
<td>Eleusine indica</td>
<td>19.6</td>
<td>1.64</td>
<td>0.919</td>
<td>0.617</td>
<td>0.336</td>
<td>0.172</td>
<td>5.343</td>
<td>0.714</td>
</tr>
<tr>
<td></td>
<td>II</td>
<td>Potentilla anserine</td>
<td>20.4</td>
<td>1.69</td>
<td>1.363</td>
<td>0.878</td>
<td>0.410</td>
<td>0.115</td>
<td>11.85</td>
<td>1.072</td>
</tr>
<tr>
<td></td>
<td>III</td>
<td>Artemisia argyi</td>
<td>21.42</td>
<td>1.95</td>
<td>0.412</td>
<td>0.312</td>
<td>0.156</td>
<td>0.070</td>
<td>5.862</td>
<td>0.842</td>
</tr>
<tr>
<td></td>
<td>IV</td>
<td>Unplanted Soil</td>
<td>22.47</td>
<td>1.77</td>
<td>0.566</td>
<td>0.435</td>
<td>0.207</td>
<td>0.065</td>
<td>8.649</td>
<td>1.158</td>
</tr>
</tbody>
</table>

Note: d₁₀, d₃₀, d₅₀, d₆₀ are values corresponding to 10%, 30%, 50%, and 60% finer by weight, respectively; Cu is uniformity coefficient, Cu = d₆₀/d₁₀; and Cc is curvature coefficient, Cc = d₅₀/d₁₀ × d₆₀

The moisture content and density of sites I and II are similar, and the two parameters of sites III and IV are only slightly different from each other, thereby
suggesting the similarity of hydraulic conditions of each small watershed gully. Grain size accumulation curves of the four samples were also obtained through the sieving test, as shown in Fig. 6. Speculation indicates that the soil of all the four sites is mealy sand. Meanwhile, the curves of sites Ⅱ and Ⅳ are smooth and continuous. Simultaneously, the two samples satisfied $C_u \geq 5$ and $C_c = 1-3$ based on the Table 1. Therefore, the two samples are effectively graded combined. In order to analyse the results more conveniently, we idealize that the test site conditions of four samples are similar.

![Grain size accumulation curve of different samples](image)

**Fig. 6** Grain size accumulation curve of different samples

### 2.3 In-situ horizontal extrusion tests

The horizontal extrusion test is a method to measure the shear resistance of the cubic sample by applying horizontal thrust to facilitate sample sliding. The test apparatus mainly comprises three parts: the reaction, thrusting and stressful parts (Fig. 7). The reaction part includes unexcavated soil, a crosstie and a steel plate. The most important component of the thrusting part is the jack, which applies the force obtained by the oil pressure gauge. The centre of the jack should be placed at 1/3 height and 1/2 width of the sample. The main body of the stressful part is the sample, but crosstie and...
steel plates are placed in front of the sample to distribute the applied force evenly. As Fig. 5 showed, two transparent plates are set at the two sides of the sample to limit the lateral deformation and be useful to record the process of cracking during the test.

Fig. 7 In-situ horizontal extrusion test schematic: 1-crosstie; 2-jack; 3-steel plate; 4-oil pressure gauge; 5-failure soil; 6-slip circle; 7-soil sample

The jack was pressed at uniform rate during the test to apply the thrust force, and the oil pressure was recorded at intervals of four presses. The pressure readings usually gradually increase from the initial state and then drop after the peak until it stabilises. Therefore, a group of tests is considered completed when the above processes are experienced.

Cracks on both lateral sides as well as the surface were recorded after finishing the test. The slip circle (Fig. 8) of the sample was drawn by fitting the two lateral cracks, and then shear parameters, including the apparent cohesion $c$ and friction angle $\phi$, were calculated as follows. The failure soil is divided into several blocks with equal spacing according to the manual acquirement, and the gravity per unit of each block was calculated.

\[ g_i = a_i h_i \gamma, \]

where $a_i$ is the width of each block, $h_i$ is the height of the centre line of each
block and $\gamma$ is the volumetric weight of soil. The values of $c$ and $\varphi$ of the sample are then respectively calculated by Eqs. (2) and (3). Peak thrust force was selected as $Q_{\text{max}}$ considering the calculation of shear parameters, and the optimal value was chosen as $Q_{\text{min}}$ in the following two ways according to the actual situation: (1) thrust force at which the gauge reading dropped to a constant value after the peak; (2) thrust when the first crack appeared.

$$\tan \varphi = \frac{Q_{\text{min}} \sum_{i=1}^{n} g_i \cos \alpha_i - \sum_{i=1}^{n} g_i \sin \alpha_i}{Q_{\text{min}} \sum_{i=1}^{n} g_i \sin \alpha_i + \sum_{i=1}^{n} g_i \cos \alpha_i},$$  \hspace{1cm} (2)

$$c = \frac{Q_{\text{max}} - Q_{\text{min}}}{G \sum_{i=1}^{n} g_i \sin \alpha_i + \sum_{i=1}^{n} g_i \cos \alpha_i} \left[ \left( \sum_{i=1}^{n} g_i \cos \alpha_i \right)^2 + \left( \sum_{i=1}^{n} g_i \sin \alpha_i \right)^2 \right],$$  \hspace{1cm} (3)

where $g_i$ is the gravity of the $i$-th block (kN), $G$ is the gravity of the sliding body, $\alpha_i$ is the angle between the sliding surface of the $i$-th block and the horizontal plane ($^\circ$), $l_i$ is the length of the $i$-th sliding line (m) and $B$ is the width of the sliding body (m).

![Fig. 8 In-situ horizontal extrusion test calculation by slices method](image)

3. Results

3.1 Surface failure patterns

The surface cracks of the four samples are shown in Fig. 9. In comparison, cracking of the unplanted soil sample is more serious than that of the root–soil samples. Three main tensile cracks paralleled to the direction of maximum principal stress run...
through the surface layer and accompanied by multiple shear cracks with different lengths (Fig. 9(a)). Different root types contribute to various surface failure patterns. No evident cracking was observed on the surface of the Eleusine indica sample based on the reinforcement and wrapping of fibrous roots (Fig. 9(b)). Similarly, Artemisia argyi can prevent the shallow soil from cracking owing to its developed lateral roots (Fig. 9(d)). However, as a typical tap root system herb, the Potentilla anserina sample is the most damaged in the three root–soil samples with two cracks approximately 1 cm wide paralleled to the maximum principal stress (Fig. 9(c)).

Fig. 9 Diagrams of surface failure patterns of four samples: (a) Unplanted soil sample, (b) Eleusine indica sample, (c) Potentilla anserine sample and (d) Artemisia argyi sample.

3.2 Lateral failure patterns

Fig. 10 shows the different degrees of cracking for the four samples. The unplanted soil sample is the most damaged with many long parallel tensile cracks through both lateral sides. Three long tensile, two short tensile and five short shear cracks are...
concentrated in the bottom region of the sample on the right side, whilst two long tensile cracks together with five short tensile cracks and three shear cracks are concentrated within 20 cm below the surface on the left side (Fig. 10(a)). Lateral cracking of the root–soil sample is less than that of the unplanted soil considering the quantity and degree of cracking. Only two cracks are observed on both sides of the specimen for Eleusine indica sample, and the cracks are mostly concentrated in the middle and bottom part of the sample where the root system could not extend to (Fig. 10(b)). The cracks of the two tap root system samples on the lateral sides are more than that of the Eleusine indica sample, but their cracks and failure behaviours are different. The Potentilla anserine sample demonstrated two and three long tensile cracks respectively distributed evenly on the left and right sides, and the cracks are approximately 90 cm long, thus mostly penetrating the sample. Furthermore, cracks still emerge in the region with roots due to the weak interfaces between the coarse tap roots and soil (Fig. 10(c)). The Artemisia argyi sample revealed that most short cracks have a length of only less than 70 cm. Moreover, cracks are gradually turning narrow or terminated when extended to the region with roots (Fig. 10(d)), indicating that the existence of root systems inhibits crack propagation.
Fig. 10 Diagrams of lateral failure patterns of four samples: (a) Unplanted soil sample, (b) Eleusine indica sample, (c) Potentilla anserine sample and (d) Artemisia argyi sample.

The slip circle of the four samples is shown in Fig. 11. The figure reveals that the initiation of the slip circle of unplanted soil is close to the bottom of the sample, and the area above the slip circle is approximately 1453 cm² (Fig. 11(a)). The position of the slip circle initiation for the root–soil samples is considerably higher than that of the unplanted soil, and the areas above the slip circle are 1352, 1464 and 1097 cm² respectively for Figs. 11(b), (c) and (d). Amongst these areas, only the failure area of the Potentilla anserine sample is slightly larger than that of unplanted soil, and that of the Eleusine indica and Artemisia argyi samples are all smaller than that of the
unplanted soil, especially for the Artemisia argyi with abundant lateral roots. These results indicate that the root system is helpful in preventing damage. Notably, despite not extending to the slip circle, some roots can still reinforce the soil similar to a fibre to avoid cracking and resist deformation, as illustrated by Fan and Su (2008).

**Fig. 11** Diagrams of slip circle of four samples: (a) Unplanted soil sample, (b) Eleusine indica sample, (c) Potentilla anserine sample and (d) Artemisia argyi sample

### 3.3 Thrust force–displacement curves

**Fig. 12** shows the thrust force–displacement curves of the four samples. Two types of curves are found between the unplanted soil and root–soil samples, that is, strain softening for unplanted soil and strain hardening for root–soil samples. The curve of the unplanted soil can be divided into three stages: rising, stable and declining, which shows a strain-softening behaviour. Unplanted soil has a high thrust force when the shear displacement is less than 3 mm, but its shear resistance capability rapidly drops upon its entry to the failure stage, indicating a brittle feature. The thrust force–displacement curves show different degrees of strain-hardening characteristics for root–soil samples. The constant rising of the curves of two tap root system samples indicates a strong strain-hardening effect. The curve for the Eleusine indica sample comprised...
similar rising and stable stages because unplanted soil indicates a relatively weak influence on strain hardening. Conversely, Potentilla anserina maintained a strong strain-hardening effect in the entire process and the thrust force continuously increased with the displacement at an approximately constant rate until the test was terminated in accordance with the handbook instructions. The increasing of thrust force for the Artemisia argyi sample gradually slowed down after the initial rapid rising stage. The thrust force increased and then suddenly dropped when the deformation exceeded 30 mm possibly because the stress-borne tap roots reached the ultimate force and then suddenly broke. Moreover, the unplanted soil initially reached the peak thrust force when the deformation has reached 47.5% of the total displacement. Meanwhile, the three root–soil samples all reached the peak thrust force in the late stages of the entire test displacement, especially for the two tap root system samples, convincingly demonstrating that they have a stronger impact on resisting large deformation than fibrous root system.
Fig. 12 Thrust–displacement curve and ratio of $d_{u-f}$ to $d_t$ of each sample: $d_{u-f}$ - displacement corresponding to ultimate force; $d_t$ - total displacement

The values of $c$ and $\phi$ of each sample are calculated by Eq. (3) and shown in Fig. 13. The results indicate that the $c$ values of the Eleusine indica, Potentilla anserine and Artemisia argyi samples are respectively 1.08, 0.86 and 1.26 times that of unplanted soil sample and 0.75, 1.26 and 1.24 times for the $\phi$ value. Notably, the values of $\phi$ may be overestimated because the slip circle is slightly long and gentle after fitting to
consider the situation of cracks on both sides comprehensively.

**Fig. 13** Shear strength parameters of four samples

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4. Discussion

4.1 Reinforcement of roots on soil

The results in Section 3 show that the presence of roots in soil samples has a positive effect on shear resistance and reducing soil crack development. Some similar phenomena can be summarised by comparing the results of the large-scale in-situ horizontal extrusion tests with previous different types of tests.

The thrust force–displacement curves in this paper show a transformation of medium from strain softening to strain hardening. The unplanted soil specimen is the fastest to reach the peak force compared with others. This result indicates the collapse of brittle failure with rapid thrust force as the displacement increases, which provides a typical strain-softening curve. On the contrary, a high force is maintained due to the presence of the root upon termination of the test according to the handbook instructions, which shows a strain-hardening effect in the root–soil samples. These results and phenomena are consistent with those of the in-situ direct shear (i.e. Lu et al., 2016, Yu et al., 2013) with assumed shear plane and the laboratory direct shear tests with small specimen size (i.e. Ge et al., 2014). The results presented in Yu et al. (2013) indicate
the integration of the shear force–time curves of unplanted soil and root–soil samples under in-situ direct shear test as shown in Fig. 14. The figure reveals that the failure process of the unplanted soil shows distinct increasing, stable and dropping stages of the shear force. Moreover, the curves of the two root–soil samples continuously increased, indicating a strain-hardening characteristic, which shows the same regularity of the thrust–displacement curve in this study. Therefore, the roots can improve the shear resistance of the test soil and promote the transformation of the soil to strain hardening due to its network coating, vertical reinforcement and mechanical properties. However, the roots of Eleusine indica in this experiment are remarkably thin and short fibrous roots and cannot provide substantial improvements to the shear resistance of the soil–root system. Thus, the resisting shear force is still mainly from soil.

Fig. 14 Shear force–time curve of soil and root–soil samples by direct shear test (Yu et al. 2013)

The effect of roots can also be found in the results of the test phenomena. Figs. 9 and 10 show that roots can reduce cracking on the bilateral sides and the surface of the sample and limit the length and width of the cracks. These reinforcement effects of root on soil weakened with the decline of root density, which is similar to the results presented in Abernethy and Rutherfurd (2001).
The results of the characteristic curves and test phenomena also indicate that the existence of roots changes the natural cementing conditions of the soil particles, reinforces the soil by forming a whole with soil particles and helps the soil body resist the shear force as a separate anchoring tool.

4.2 Effects of different root systems on the physical and mechanical properties of soil

The above results show that the existence of roots has a positive effect to the shear, but different root systems contribute to various behaviours. The fibrous root system has a significant effect on reducing the formation and development of shallow cracks but a minimal impact on the improvement of shear resistance of the soil. The tap root system promotes the transformation from strain softening to strain hardening and increases the shear resistance. However, this system may create several cracks on the surface or lateral sides due to the existence of the thick taproot. However, even the same root system can produce different failure characteristics, which may result from the different proportions of thick taproot and lateral roots. The root system of Potentilla anserine is dominated by the taproot with few lateral roots, whilst abundant lateral roots accounted for a large proportion of the root system of Artemisia argyi. The structure cemented by the tuberous taproot and soil for Potentilla anserine is slightly firm, thus resulting in easy cracking on the surface when subjected to shear. By contrast, Artemisia argyi is effective in controlling the cracks on the surface owing to the developed lateral roots, and this trait is useful for guiding the selection of slope protection plants.
The comprehensive analysis of the results of the three root–soil tests revealed the different effects of fibrous and taproot on soil. Thus, fine fibrous roots can form a complex with soil, which may be attributed to the network by interlacing and wrapping the soil particles through its secreted mucus (Ge et al., 2014; Gyssels and Poesen, 2003), thus reducing cracks. The effect of fibrous roots focuses on the optimisation of reducing cracks but has minimal improvements considering soil strength, as observed in the thrust force–displacement curve of Eleusine indica. By contrast, taproot with large diameters are slightly lignified epidermis (Pollen, 2007; Shen et al., 2021). Therefore, these roots can improve soil strength owing to the compression and anchorage and jointly resist the shear force with the soil as a stress component due to its strength and friction with soil particles. The complex comprising thick taproot and soil has strain-hardening characteristics when subjected to shear, similar to that shown in the thrust force–displacement curve of Potentilla anserine and Artemisia argyi. Additionally, the comparison of the curves of the two root–soil samples reveals that the sudden drop of the thrust force in curve of Artemisia argyi shows that the stress-bearing taproot is broken.

Considering the characteristic parameters of shear, some scholars suggested that roots had considerable influence on the values of \( c \) but minimal effect on the values of \( \phi \) based on several studies of different tests, such as triaxial compression test and direct shear test of root–soil (Waldron, 1977; Ali and Osman, 2007; Osman et al., 2008; Veylon et al., 2015). This study revealed that fibrous roots can promote the
transformation of soil from frictional to cohesive materials and induce an increase in
the $c$ and decrease in the $\phi$ similar to Eleusine indica. In the test with Potentilla anserine,
the taproot with a diameter of 6 mm demonstrates a weak interface with soil, thus
decreasing the value of $c$ but increasing the value of $\phi$ due to the additional friction with
soil particles. As a plant with taproot and abundant lateral roots, Artemisia argyi
simultaneously increased the values of $c$ and $\phi$ of the root–soil sample.

The above discussions provide two types of root–soil deformation mode: ‘fibrous
root–soil deformation’ and ‘tap root–soil deformation’. Soft and fine fibrous roots can
wrap and net soil particles through the stickiness of secreted mucus, which is effectively
reduce cracking in the failure process of the soil. However, the effect of roots on
improving the strength of the soil is negligible. Fig. 15a shows that fibrous root has a
coupled activity and a fast deformation linkage with soil particles due to the low
stiffness difference, and the extreme deformation and tensile failure will occur shortly
when subjected to shear. Differently, coarse tap root can anchor the soil due to its large
diameter and slightly lignified epidermis, improving the shear resistance of the root–
soil complex. The stiffness between the tap root and soil varied wildly; therefore, tap
root can resist soil shear due to its strength and slight deformation at the early stage.

Soil will break before the root–soil complex loses its strength with continuous shearing
and the tap root will be the main shear stress-borne component at the later stage until it
reaches the ultimate deformation failure (Fig. 15b). This multistep process improves
the shear strength and resistance to large deformation of the root–soil. Notably, the
root–soil sample fails mostly before the root exerts its full tensile or shear strength (Wu and Watson, 1998; Fan and Tsai, 2016; Operstein and Frydman, 2000; Giadrossich et al., 2017). Therefore, tap root system plants with thick tap roots and abundant fibrous lateral roots are the most suitable for slope protection.

Fig. 15 Two types of conceptual diagram: (a) ‘Fibrous root–soil deformation’ mode; (b) ‘Tap root–soil deformation’ mode

5. Conclusions

Four in-situ horizontal extrusion tests were conducted in this study on two types of root systems, namely fibrous and tap roots, for three plants (Eleusine indica, Potentilla anserine and Artemisia argyi). The influence of the different types of root systems on the shear failure characteristic was explored by analysing the thrust–displacement curves and failure patterns of samples. Some main conclusions are summarised as follows.

(1) The existence of roots promotes the transformation of soil from a strain-softening to a strain-hardening medium, improves resistance to deformation and
418 reduces cracking and deformation during shearing.

419 (2) The influence of roots on the soil behaviour varies with the type of root system. 

420 Fibrous root systems strongly impact the wrapping and netting of the soil and 
421 effectively reduce the soil cracks. The improvement of shear force is not observed 
422 despite its capability to increase the cohesion value slightly. However, the tap root 
423 system improves the effect of strain hardening and increases the shear resistance, and 
424 this system with long and rich lateral fibrous roots behaves better on resisting cracks 
425 than that with taproot as the dominant. 

426 (3) Through the allocation of plants with different types of root systems, ecological 
427 protection methods should be considered to meet the different objectives of slope 
428 protection, such as preventing soil cracking, reducing deformation and improving 
429 strength.

6. Acknowledgements

432 The authors wish to acknowledge financial support from the Strategic Priority 
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437 should also be expressed to the China–Pakistan Joint Research Centre on Earth 
438 Sciences that supported the implementation of this study.
7. References Cited


Coutts, M.P., 1983. Development of the structural root system of Sitka spruce. Forestry,


plant root traits for protecting natural and engineered slopes against landslides.


Table list (Total of 1)

Table 1 Basic physical parameter of four samples

<table>
<thead>
<tr>
<th>Valley</th>
<th>Site</th>
<th>Sample</th>
<th>Moisture content (%)</th>
<th>Density g/cm³</th>
<th>d60 mm</th>
<th>d50 mm</th>
<th>d30 mm</th>
<th>d10 mm</th>
<th>Cu</th>
<th>Cc</th>
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<tr>
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<td>I</td>
<td>Eleusine indica</td>
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<td>II</td>
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<td>0.410</td>
<td>0.115</td>
<td>11.85</td>
<td>1.072</td>
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<td>Fencha gully</td>
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<td>0.312</td>
<td>0.156</td>
<td>0.070</td>
<td>5.862</td>
<td>0.842</td>
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<td>IV</td>
<td>Unplanted Soil</td>
<td>22.47</td>
<td>1.77</td>
<td>0.566</td>
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<td>0.207</td>
<td>0.065</td>
<td>8.649</td>
<td>1.158</td>
</tr>
</tbody>
</table>

Note: d₁₀, d₃₀, d₅₀, d₆₀ are values corresponding to 10%, 30%, 50%, and 60% finer by weight, respectively; Cᵤ is uniformity coefficient, Cᵤ = \( \frac{d₆₀}{d₅₀} \), and Cₗ is curvature coefficient, Cₗ = \( \frac{d₃₀}{d₁₀ \times d₆₀} \).
Figure list (Total of 15)

Fig. 1 Typical diagram of tap-root-system and fibrous-root-system (Jin, 2006): A-jute; B-maize

Fig. 2 In-situ test site location (from Google Earth)

Fig. 3 Herbaceous plants and roots used in the experiment: (a) Eleusine indica; (b) Potentilla anserine; (c) Artemisia argyi

Fig. 4 Schematic diagram of sample size/mm

Fig. 5 Samples for horizontal extrusion test: (a) Unplanted soil sample, (b) Eleusine indica sample, (c) Potentilla anserine sample, (d) Artemisia argyi sample

Fig. 6 Grain size accumulation curve of different samples

Fig. 7 In-situ horizontal extrusion test schematic diagram: 1-crosstie; 2-jack; 3-steel plate; 4-oil pressure gauge; 5-failure soil; 6-slip circle; 7-soil sample

Fig. 8 In-situ horizontal extrusion test calculation by slices method

Fig. 9 Diagrams of surface failure patterns of four samples: (a) Unplanted soil sample, (b) Eleusine indica sample, (c) Potentilla anserine sample, (d) Artemisia argyi sample

Fig. 10 Diagrams of lateral failure patterns of four samples (a) Unplanted soil sample, (b) Eleusine indica sample, (c) Potentilla anserine sample, (d) Artemisia argyi sample

Fig. 11 Diagrams of slip circle of four samples (a) Unplanted soil sample, (b) Eleusine indica sample, (c) Potentilla anserine sample, (d) Artemisia argyi sample

Fig. 12 Thrust - displacement curve and ratio of $d_{u-f}$ to $d_t$ of each sample: $d_{u-f}$ - displacement corresponding to ultimate force; $d_t$ - total displacement
Fig. 13 Shear strength parameters of four samples

Fig. 14 Shear force-time curve of soil and root soil samples by direct shear test (Yu et al. 2013)

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声明

本文首次基于植物学分类选取了不同根系类型的植被，基于此开展了根系土的原位推剪试验。水平推动剪切不会预设剪切面，比常用的直接剪切方法更符合实际破坏过程。通过水平推剪试验结果可直观对比不同类型根系在抗剪方面的作用。本研究可用于指导防止浅层土体侵蚀破坏的护坡植被选取工作。
Statement

In this paper, we selected three different plants of two types of root system according to the classification of *Botany* for the first time and conducted the in-situ horizontal extrusion shear test of root-soil samples. Horizontal extrusion test does not preset shear plane, which is more consistent with the actual failure process. Different effects of various types of root system can be compared intuitively by analyzing the results of the tests. This study can be used to provide guidance for vegetation selection to prevent the shallow soil erosion.
Fig. 1 Typical diagram of tap root and fibrous root systems (Jin, 2006): A-jute; B-maize;
69x43mm (300 x 300 DPI)
Fig. 2 In-situ test site location (from Google Earth)

139x100mm (600 x 600 DPI)
Fig. 3 Herbaceous plants and roots used in the experiment: (a) Eleusine indica; (b) Potentilla anserine; (c) Artemisia argyi

189x43mm (600 x 600 DPI)
Fig. 5 Samples for horizontal extrusion test: (a) Unplanted soil sample, (b) Eleusine indica sample, (c) Potentilla anserine sample, (d) Artemisia argyi sample

139x36mm (600 x 600 DPI)
Fig. 6 Grain size accumulation curve of different samples

69x40mm (600 x 600 DPI)
Fig. 7 In-situ horizontal extrusion test schematic: 1-crosstie; 2-jack; 3-steel plate; 4-oil pressure gauge; 5-failure soil; 6-slip circle; 7-soil sample

69x32mm (300 x 300 DPI)
Fig. 8 In-situ horizontal extrusion test calculation by slices method

69x26mm (300 x 300 DPI)
Fig. 9 Diagrams of surface failure patterns of four samples: (a) Unplanted soil sample, (b) Eleusine indica sample, (c) Potentilla anserine sample and (d) Artemisia argyi sample

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189x146mm (300 x 300 DPI)
Fig. 11 Diagrams of slip circle of four samples: (a) Unplanted soil sample, (b) Eleusine indica sample, (c) Potentilla anserine sample and (d) Artemisia argyi sample

140x50mm (600 x 600 DPI)
Fig. 12 Thrust–displacement curve and ratio of du–f to dt of each sample: du–f - displacement corresponding to ultimate force; dt - total displacement
Fig. 13 Shear strength parameters of four samples

69x38mm (600 x 600 DPI)
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