

Stress-dilatancy relationship of rooted soil: shear mode effect

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ABSTRACT: Direct shear test (DST) and simple shear test (SST) have been commonly used to measure the shear strength of soils. DST, favoured for its simplicity, has been almost exclusively used for testing rooted soils but this method imposes a predefined shear plane, incapable of capturing the stress conditions of soil element before slope failure occurs. In contrast, SST better simulates shear behaviour but has never been used before to assess the root effects on soil shear strength and dilatancy. This study conducted DSTs and SSTs on sandy soil reinforced with vetiver grass roots (*Chrysopogon zizanioides* L.) to measure the stress-dilatancy relationships. Results revealed that DST consistently overestimated shear strength and dilatancy, with effective cohesion of rooted soil often more than 100% of that obtained from SST. The stress-dilatancy analysis revealed that DST required higher mobilised stress to reach the maximum dilatancy than SST, whilst in rooted soils, the stress ratio continued to rise beyond the maximum dilatancy due to additional energy dissipation from the mobilisation of root tensile properties. These findings emphasise the need for caution when using DST for evaluating the shear behaviour of rooted soils and highlight the importance of considering both root cohesion and dilatancy effects in stability assessments and engineering applications.

Keywords: direct shear test; simple shear test; rooted soil; stress-dilatancy; sandy soil

1 INTRODUCTION

In rooted soils, plant roots provide mechanical reinforcement to soil by mobilising their tensile and/or bending resistance upon shearing, thereby enhancing soil shear strength. In the past 40 years, root reinforcement has been almost exclusively evaluated through direct shear tests (DSTs). Yet, existing studies have shown that failure surfaces in the soil tested in direct shear box initially develop diagonally and later rotate under the boundary constraints (Potts et al., 1987), leading to non-uniform stress-strain distributions and overestimation of shear strength. An alternative is the simple shear test (SST), which is considered more representative of field stress conditions during failure initiation. Unlike DSTs, SSTs do not impose a shear plane but instead allow principal stress axes to rotate and failure to occur along the natural weakest plane. Moreover, SSTs offer advantages for evaluating soil dilatancy. In DSTs, dilatancy is estimated from vertical displacements of the entire specimen, but only the mid-height zone experiences true simple shear (Potts et al., 1987). By contrast, SSTs generate more uniform volumetric behaviour across the soils (Potts et al., 1987), making them better suited to studying stress-strain and stress-dilatancy relationships under practical conditions.

Although extensive studies have compared the shear responses obtained from DST and SST for bare soils

(Fei and Zekkos, 2018), such comparisons for rooted soils are absent. This study investigates the shear behaviour of rooted soils measured under both DST and SST conditions and shows how shear mode would affect the stress-dilatancy relationships of rooted soils.

2 MATERIALS AND METHODS

2.1 Test apparatus and materials

A large-size Swedish Geotechnical Institute (SGI) type simple shear apparatus was used in this study to measure the shear behaviour of bare and rooted soils (Figure 1). Each specimen was cylindrical, with a diameter of 300 mm and a maximum height of 100 mm, giving a D/H ratio of at least 3, which exceeds the ASTM D6528-17 requirement of 2.5 and thus minimises stress non-uniformity. To reduce boundary friction, the apparatus employed a stack of 20 Teflon-coated aluminium rings, each 5 mm thick. For DSTs, the stacked rings could be replaced with a rigid split box (Figure 1).

The soil used in all tests was Toyoura sand, which is a clean, uniformly graded sand with a mean particle size of 0.2 mm. This soil type was selected because its mechanical properties are well documented in the literature, and the sand is suitable for producing samples with controlled conditions by the dry deposition method. The

plant chosen was for testing was vetiver grass (*Chrysopogon zizanioides* L.). Vetiver is sterile and reproduces only through clumps, eliminating risks of invasive spread. Its root system is deep and fast-growing, extending up to 3 m within a year (Mickovski and van Beek, 2009), making it highly effective for shallow slope reinforcement. Laboratory tensile tests have shown that vetiver roots possess high mechanical strength, with tensile modulus and tensile strength of 161.6 ± 8.98 MPa and 21.4 ± 1.03 MPa, respectively (Wu et al. 2024).

2.2 Test procedures

The sample preparation method of bare and rooted soil was the dry deposition method (Karimzadeh et al., 2021), achieving to an initial void ratio of 0.73 and a relative density (RD) of 64%. For rooted specimens, vetiver roots were cut into 100 mm long segments with diameters of 1.0–1.8 mm, and they were orientated vertically and then adhered on the base of the sample container. Each root segment was scanned using an EPSON STD4800 scanner and analysed with Pro-WinRHIZO software to quantify root volume ratio (RVR) of 0.6% in each rooted sample. The tests were conducted under controlled room humidity.

The test programme comprised 12 experiments, with six SSTs and six DSTs. For each shear mode, three bare and three rooted specimens were subjected to vertical compression under K_0 conditions at normal stresses of 30, 50, and 100 kPa.

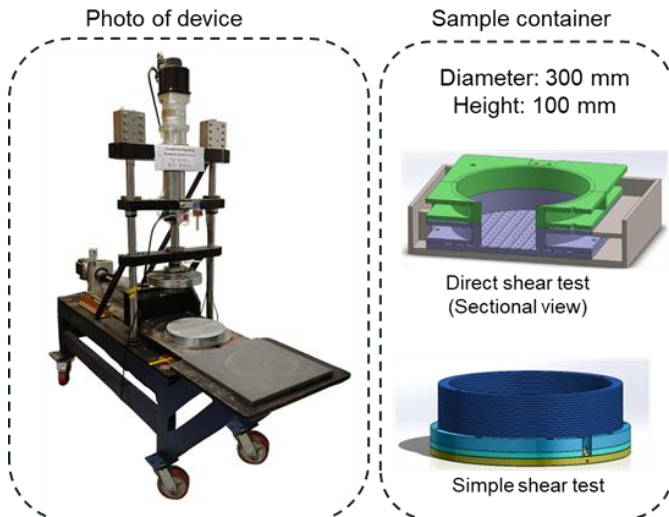


Figure 1. Experimental setup and sample container

3 RESULTS

3.1 Shear strength

Figure 2 depicts the shear stress–displacement relationships of the bare specimens tested under both DST and SST conditions. Although SSTs allow the determination of shear strain, the results are expressed herein in shear displacement for direct comparison with the DST results. At all the normal stresses, the shear strength obtained from the DSTs was consistently higher than that from the SSTs. This systematic difference can be interpreted with reference to Rowe's (1962) dilatancy theory, which relates shear strength to energy dissipation mechanisms within the soil.

$$\frac{R}{D} = \frac{\tan(\phi_\mu + \beta)}{\tan \beta} \quad (1)$$

where R and D are the stress ratio and dilatancy (dilatation as positive); R/D means the ratio of input and output energy; ϕ_μ is the interparticle friction angle; and β is the particles sliding direction to the major principal stress axis. Under DST condition, the soil is artificially constrained to fail along a horizontal plane, which may not coincide with its natural weakest plane. This condition imposed constraint demands higher energy to initiate and propagate failure. At the microscopic level, particles in DST must overcome greater interparticle friction and stronger interlocking, leading to higher R/D . By contrast, SSTs allow the soil to fail along its natural plane of weakness β , thereby requiring less energy input and resulting in lower R/D .

The presence of roots altered these behaviours. For a given normal stress and shear mode, rooted specimens consistently exhibited higher shear strength than their bare counterparts (Figs 2(a) and (b)), attributed to root reinforcement. During shearing, roots mobilise their tensile strength through load transfer at the soil–root interface. Consequently, input work is dissipated not only through soil displacement and particle friction but also through root elongation (Schwarz et al., 2013).

Interestingly, the differences between DST and SST responses became more pronounced in the rooted soils than in the bare soils. Rooted direct-shear specimens exhibited a pronounced strain-hardening effect. Their shear stress continued to increase without reaching a plateau or critical state, even after displacements approaching 30 mm. This behaviour led to an overestimation of shear strength relative to the simple shear results (Figure 2 (b)). In contrast, bare specimens, regardless of the shear mode, tended to develop strain hardening only until they approached a plateau or critical state.

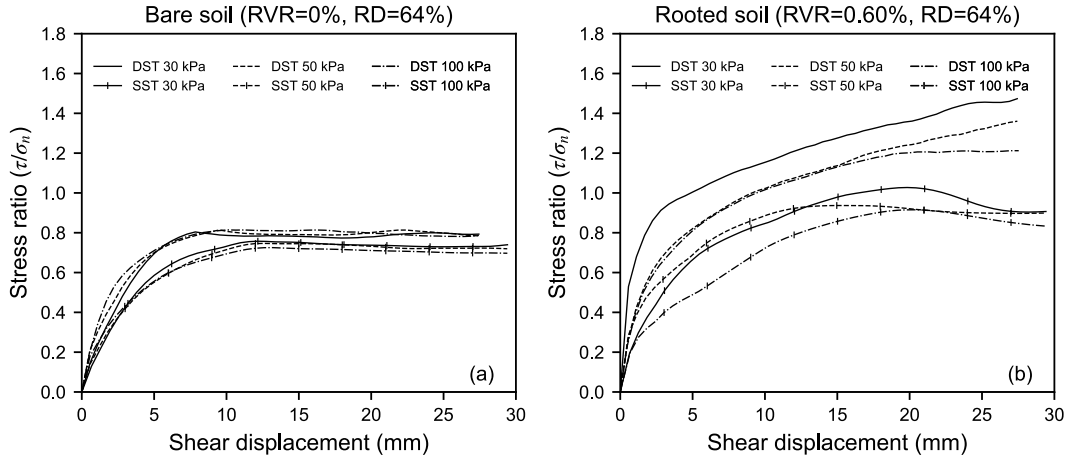


Figure 2. Stress ratio (τ/σ_n)–shear displacement of soils under direct shear tests (DST) and simple shear tests (SST) at normal stresses of 30, 50, and 100 kPa in (a) bare soil ($RVR = 0\%$, $RD = 64\%$); (b) rooted soil ($RVR = 0.60\%$, $RD = 64\%$)

3.2 Stress-dilatancy relationships

The stress–dilatancy behaviour of granular soils under plane strain conditions can be interpreted using saw-tooth model (Wood, 1990). In this model, all the work input of shear force (Q) is assumed to dissipate as friction, with the frictional energy loss governed by the normal load (P) and a frictional constant (μ). This condition leads to the following expression:

$$\frac{Q}{P} + \frac{\delta y}{\delta x} = \mu \quad (2)$$

where Q/P represents the mobilised friction, expressed as $\tan\phi'_m$; and ϕ'_m is the mobilised friction angle. The ratio $\delta y/\delta x$ denotes volumetric dilatancy, calculated as $-\tan\psi$, where ψ is the dilatancy angle. Here, δx and δy corresponds to the horizontal and vertical displacements, respectively.

As shown in Figure 3, both bare and rooted specimens contracted at low mobilised stress ratios (Q/P) and then dilated as shearing progressed. For the bare specimen, the value of μ was 0.68 for SST and 0.74 for DST, indicating that the latter required higher energy input and frictional energy loss due to shearing along non-weakest planes. Moreover, DST reached the maximum dilatancy at a higher stress ratio than SST, reflecting greater resistance to particle rearrangement.

In the rooted specimen, the phase transformation (i.e. from contraction to dilation) persisted, but after reaching the maximum dilatancy, the stress ratio continued to rise instead. This behaviour can be explained by the saw-tooth energy framework: in bare soil, energy is dissipated mainly through friction and particle rearrangement, whereas in the rooted soil additional energy is consumed by roots through elongation and root–soil interfacial shearing. Consequently, even when volumetric dilatancy decreases, the mobilised stress ratio rises due to the increasing contribution of root resistance. This coupling between soil friction and root reinforcement

modifies the energy balance, shifting the stress–dilatancy relationship upward and producing a distinct difference between bare and rooted cases, meaning a stress-dilatancy relationship for rooted soil is required to interpret the experimental data.

3.3 Shear strength parameters

Table 1 presents the shear strength parameters of bare and rooted specimens under both direct shear and simple shear modes, together with the corresponding effective cohesion (c') and effective peak friction angle (ϕ'_p). The addition of roots increased the effective cohesion from zero to 10.8 kPa in the DSTs and to 4.5 kPa in the SSTs. Accordingly, the root cohesion (c_r) was 10.8 and 4.5 kPa, respectively. In addition to cohesion, roots also enhanced ϕ'_p by 19.4% in DST and 12.2% in SST. These increases are consistent with trends reported in previous studies (Yildiz et al., 2018).

Table 1. Shear strength parameters

Test	Cohesion (kPa)	Peak friction angle (°)	Max dilatancy angle (°)
DST B	0.0	40.2	8.7
DST R	10.8	48.0	9.6
SST B	0.0	36.6	6.6
SST R	4.5	41.1	8.1

The observed changes in ϕ'_p can be explained by strength anisotropy theories (Gao and Zhao, 2013). Variations in friction angle depend on the relative orientation between roots and the major principal stress direction. DSTs typically involve a larger rotation of the major principal stress axis compared with SSTs (Oda, 1975). As a result, the stress orientation during direct shear becomes more perpendicular to the root alignment, leading to greater mobilisation of shear resistance and a higher ϕ'_p .

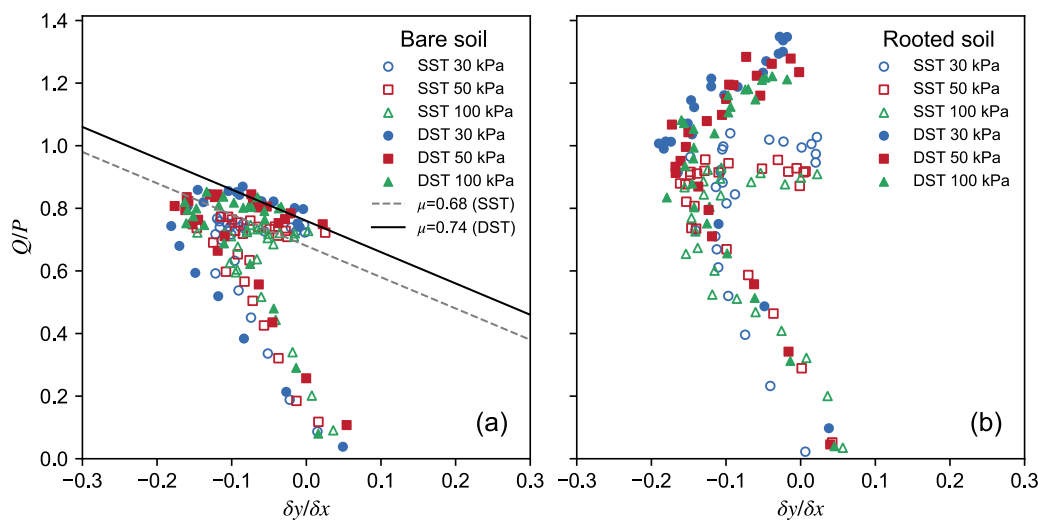


Figure 3. Stress–dilatancy relationships of (a) bare soil and (b) rooted soil from direct shear tests (DST) and simple shear tests (SST) under normal stresses of 30, 50, and 100 kPa

4 CONCLUSIONS

This study applied an improved simple-shear apparatus to examine the shear behaviour and stress–dilatancy responses of rooted soils. Identical specimens were tested under direct shear (DST) and simple shear (SST) conditions to evaluate differences in root reinforcement effects. Results showed that DST consistently overestimated soil strength compared with SST. For bare soils, the effective peak friction and dilatancy angles from DST (40.2° and 8.7°) were about 10% and 30% higher, due to forced shearing along a predefined plane rather than the soil’s natural weakness plane. For rooted soils, DST produced even greater overestimations, particularly in effective cohesion (exceeding 100%). Compared with SST, DST reached the maximum dilatancy at a higher stress ratio, and in rooted soil the mobilised stress ratio continued to increase beyond the maximum dilatancy due to additional resistance provided by roots through elongation and/or interfacial shearing with soil. Future work should extend this study to the stress–dilatancy of rooted soils under saturated and unsaturated conditions.

5 ACKNOWLEDGEMENTS

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