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Monotonic and cyclic behaviour of root-reinforced sand

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Abstract

Plant roots are known to provide mechanical reinforcement to soils upon shearing and seismic loading. However, the effects of different stress paths on root reinforcement are unclear. Moreover, whether, and how, roots provide resistance to soil liquefaction upon cyclic loading have rarely been studied. The objective of this study is to conduct a series of undrained triaxial tests to investigate the monotonic and cyclic behaviour of rooted sand. Roots of vetiver grass (*Chrysopogon zizanioides* L), which has been advocated for use in shallow slope stabilisation purposes, were used for testing. The root diameters ranged between 0.3 to 1.5 mm, while the root volume ratios were 0.23%, 0.45% and 0.67%. It was discovered that the root reinforcement effect was anisotropic and path-dependent. Along the extension path when the major principal stress was perpendicular to the predominant root orientation, the root-induced increase in soil friction angle was approximately 10°. This increase was much greater than the case along the compression path where the change was minimal. The presence of roots prevented the limited flow failure (which occurred in the unreinforced sand), and the failure mode of root-reinforced soil switched to cyclic mobility. The liquefaction resistance was improved with an increase in root volume, and this improvement was more remarkable at higher cyclic stress ratios.

Keywords: Vegetation, Root reinforcement, Soil-root interaction, Stress paths, Liquefaction

Introduction

Soil bioengineering using vegetation is considered as an environmentally and ecologically friendly bio-remediation technique for resisting shallow soil slope failure against rainfall (Stokes et al. 2014; Ni et al. 2019; Switala and Wu 2018), earthquakes (Liang and Knappett 2017; Liang et al. 2020; Tanaka et al. 2021), and also for mediating the floatation of buried pipelines due to liquefaction (Wang et al. 2018). Plant roots permeated to the soil matrix form a soil-root composite and resist shearing by mobilising the roots' tensile or/and flexural properties and the soil-root interface friction (Gray and Barker 2004; Schwarz et al. 2010). In addition to mechanical reinforcement, recent research has demonstrated that the removal of soil moisture through the process of plant transpiration and root-water uptake induces soil matric suction, which in turn increases the soil shear strength (Leung et al. 2017, 2019; Boldrin et al. 2018, 2020; Switala et al. 2018; Mahannopkul and Jotisankasa 2019; Ni et al. 2019; Yildiz et al. 2019)

To reveal and understand the root reinforcement mechanisms, it is vital to identify the stress paths relevant to slope failure. Figure 1 shows a marginally stable vegetated slope and three major stress states in which their major principal stresses are rotating along a slip surface from the slope crest to toe. Soil elements near the crest and the toe of the slope are normally subjected to compression and extension, respectively. The soil elements between these two stress states, on the other hand, may be approximated as following a direct or simple shear stress path. Indeed, in the literature, most of the studies since the 1970s conducted drained, or partially-drained, direct-shear tests to investigate any changes in soil shear strength due to root reinforcement (Waldron 1977; Wu et al. 1979; Ali and Osman 2008; Jotisankasa and Taworn 2016; Yildiz et al. 2019). It is then commonly assumed that the rooted soil obeys the Mohr-Coulomb failure criterion for determining any root-induced changes in soil cohesion and friction angle. Most of the results from the direct-shear tests showed that roots increased the cohesion (known as root cohesion; (Wu et al. 1979)), whereas the friction angle remained mostly unchanged. Although the test results might well represent the behaviour of rooted soil at some locations along the failure slip, the inability of the direct-shear apparatus to control the magnitude and direction of the major and minor principal stresses makes the knowledge derived not fully transferable in describing the behaviour of rooted soils in other positions of the slip.

Triaxial testing of rooted soil is rarely reported in the literature. As far as the authors are aware, Graf et al. (2009), Rahardjo et al. (2014), Neto and Mahler (2017), Foresta et al. (2020) are the only studies that used a triaxial apparatus to investigate the shearing behaviour of root-reinforced soils under compression or/and extension stress paths. All of these studies showed that the presence of roots caused not only an increase in the cohesion but also the friction angle. In particular, the soil friction angle reported by Graf et al. (2009), who tested *Alnus incana* cultivated in moraine soil along a compression stress path, was increased by more than 5°. Neto and Mahler (2017) is the only study that compared the shearing behaviour of rooted soils between the drained compression and extension stress paths. The test results showed that the contribution of the roots to the enhancement of shear strength of rooted soil through compression and extension stress paths increased both the friction angle and cohesion. These increases were more remarkable along the extension path.

Regarding the cyclic behaviour of rooted soil, no study on the element behaviour can be found in the literature. There are published works, however, showing that plant roots can improve (i) the seismic slope performance (Liang and Knappett 2017; Liang et al. 2020) and (ii) the uplifting potential (flotation) of buried pipelines against earthquakes (Wang et al. 2018). These studies, though, used 3-D printed root analogues instead of real roots for testing in a geotechnical centrifuge. Despite the appealing reinforcement effects provided by the plant roots in these limited studies, the fundamental underlying mechanisms of root reinforcement upon cyclic loading are not clear. In particular, how the presence of roots may change the cyclic failure mechanism of soil (e.g. limited flow failure versus liquefaction) and the liquefaction resistance of soil has never been investigated before.

The objective of this study is to investigate the monotonic and cyclic behaviour of saturated root-permeated soil. Two series of undrained triaxial tests were conducted. The first series was a comprehensive set of strain-controlled undrained monotonic triaxial tests for investigating the root reinforcement effects when sheared under triaxial compression and extension paths at different effective confining pressures. The second series was a set of stress-controlled undrained cyclic triaxial tests which studied the liquefaction resistance of root-permeated soil with different amounts of root volume at various cyclic stress ratio. The first series of tests were designed to interpret and explain the cyclic behaviour observed in the second series of tests.

Materials and methods

Test materials and properties

Toyoura sand (Toyoura Keiseki Kogyo Co., 62 Ltd.), which is a uniformly graded quartz sand with subangular to angular particles free of organic matter, was used for testing. Some index properties of the sand are summarised in Table 1.

Roots of vetiver grass (*Chrysopogon zizanioides* L.; about 1.5 years old since seed germination) were selected for testing in this study. This grass species is native to India but can be found in many parts of Southeast Asian countries such as Thailand, Malaysia and Indonesia. In general, vetiver grass has an extensive and deep-rooted system (up to 5 m depth) after 12 months of growth (Ke et al. 2003; Mickovski and vanBeek 2009). Because of these appealing traits, this grass species has been advocated as an 'ecological engineer', for use in shallow slope stabilisation purposes (Stokes et al. 2014). The tensile properties of 156 Vetiver roots were measured by subjecting them to uniaxial tensile tests. It was found that the tensile elastic modulus, tensile strength at breakage and the tensile strain at breakage were 161.6 ± 8.98 MPa, 21.4 ± 1.03 MPa and 0.32 ± 0.01 mm/mm (mean $\pm$ standard error of mean), respectively.

Method of sample preparation

Two types of triaxial specimens with identical dimensions (75 mm diameter and 152 mm height) were prepared for this study, one bare (i.e. without roots) and one rooted. All the bare specimens tested were produced by the standard dry deposition method, which is known to be capable of capturing the inherent anisotropy behaviour of the soil (Miura and Toki 1982). Following the sample preparation method introduced by Ishihara (1993) and ASTM (2011) D4767, dry sand was deposited through a funnel to achieve the target dry density of 1500 kg/m^3 , which is equivalent to a void ratio of 0.73 and a relative density (RD) of 64%.

The rooted specimens, on the other hand, were prepared using the following steps. First of all, relatively straight, air-dried roots with approximate length of 160 mm and within the diameter range of 1 to 1.5 mm were collected. These roots, with some fibrous roots attached (as small as 0.3 mm; Fig. 2(a)), were scanned (Model: STD4800, EPSON scanner) in order to determine the root traits including diameter, length and volume using image analysis by the software, Pro-WinRHIZO. In this study, three root volume ratios (RVR; the ratio of total root volume to total specimen volume)

of 0.23%, 0.45% and 0.67%, were considered. These ratios fall within the typical range found in the field (Le et al. 2017; Hamidifar et al. 2018). The number of roots was manipulated until the target RVRs were achieved (i.e. with a total root volume of 1.5 cm³ for RVR=0.23%, 3 cm³ for RVR=0.45% and 4.5 cm³ for RVR=0.67%). Subsequently, these roots were attached to the bottom of a triaxial mould (Fig. 2(b)) using weak glue, which can be removed after making the specimen. Dry sand was deposited around the roots in the mould, following the same procedures as the production of the bare specimen. Since the roots occupied some soil pore space and the associated solid content could not be neglected, less amount of dry soil mass was deposited in the rooted specimens. Hence, the void ratio of the soil matrix in all of the rooted specimen was the same as that of the bare specimen, however; the total void ratio of rooted soil is lower than bare soil, in order to highlight the effects of roots on the shearing behaviour. After sand deposition, the bottom pedestal was set on the top of the specimen, and the entire mould, together with the bottom pedestal, were turned 180° slowly and gently. The bottom of the mould was removed eventually.

By the sample preparation method outlined above, the root specimens made were artificial, instead of natural through cultivation. Testing rooted specimens, however, has a major advantage that the root distribution in terms of geometry (i.e., length and diameter) and morphology (i.e., connectivity, number) is well-controlled and known. This overcomes the existing major challenges for testing cultivated samples, of which the root distribution prior to shearing (which could be destructive to the roots) is unknown, and the distribution could be significantly different from one specimen to the another due to biological variability, even when planted under the same environmental conditions. The underlying root reinforcement mechanism involved in cultivated specimens would hence be difficult to be identified. Indeed, for the vetiver grass tested in this study, the root growth direction in the field was predominantly vertical with only a little lateral spread (Mickovski and vanBeek 2009). This growth form is deemed fairly consistent with that tested in the rooted specimens. Repeated triaxial undrained compression tests were conducted to evaluate the specimen quality associated with the proposed sample preparation method. Figure 3 shows the stress-strain curves (Fig. 3(a)) and the associated development of the excess pore-water pressure (Fig. 3(b)) of the rooted specimens with an RVR of 0.45%, sheared at effective confining pressures (p_c') of 100 and 200 kPa. Two repeated tests were conducted at each confinement. The test results showed that the behaviour between each pair of

repeated tests was deemed acceptably close, given the variabilities associated with the sample preparation and root's mechanical properties. The behaviour of the rooted soil is discussed in greater detail later.

Test programme and procedures

In this study, undrained triaxial tests were performed using a computerised stress-path-controlled cyclic triaxial apparatus at the Hong Kong University of Science and Technology. The test programme included two test series. The first series was undrained monotonic tests, which were to determine the monotonic behaviour of both saturated bare and rooted specimens subjected to strain-controlled triaxial compression and extension stress paths (at an axial strain rate of 0.3%/min) at four different p_c' values (15, 30, 100 and 200 kPa). All the rooted specimens had the same RVR of 0.45%. Both the bare and rooted specimens were saturated with a back pressure of 300 kPa so that the Skempton's B value was greater than 0.95. The roots were therefore soaked. Each specimen was then isotropically consolidated to the targeted p_c' , and then sheared (following either a compression or an extension path). Note that the test data was corrected for the membrane compliance and the change of cross section of specimens, following ASTM (2011) D4767. Moreover, in all experiments, no roots were penetrated through the soil and the triaxial membrane remained fully intact. Table 2 summarises the plan for the monotonic tests.

The second series was undrained cyclic tests. Both bare and rooted specimens were tested at three different cyclic stress ratio (CSR) of 0.20, 0.25 and 0.30 but at the same p_c' of 100 kPa and frequency of 0.05 Hz. Cyclic stress ratio is defined as:

$$CSR = \frac{q_{cyc}}{2\sigma'_{3c}} \quad (1)$$

where q_{cyc} is the cyclic deviatoric stress; and σ'_{3c} is the minor effective principal stress after consolidation. After isotropic consolidation to p_c' of 100 kPa, a cyclic stress was applied until the double amplitude of axial strain ($DA\varepsilon_a$; the difference between the maximum and minimum axial strain at each loading/unloading cycle) reached 5%. This is the strain level, at which the soil structure is deemed significantly damaged, and this criterion has been commonly used to define the onset of liquefaction of a triaxial specimen (Ishihara 1993). The cyclic test plan is summarised in Table 2.

Results and discussion

Monotonic stress-strain behaviour

Figure 4(a) shows the deviator stress-axial strain curves of the bare and rooted specimens obtained from the undrained compression and extension tests at RVR=0.45% under p_c' values of 15, 30, 100 and 200 kPa. At any p_c' , both the bare and rooted specimens exhibited strain-hardening behaviour along the compression paths. This behaviour appeared to be more pronounced at lower p_c' since the soil was more dilative. Upon extension, after reaching a local peak stress, the bare specimens exhibited softening behaviour, followed by some hardening at higher strains. The rooted specimens, on the other hand, always showed strain-hardening behaviour. The observed different behaviour of the bare specimen between the two stress paths was expected because of the sand anisotropy; the direction of the major principal stress in the triaxial compression and extension tests was perpendicular and parallel to the weak plane of the sand, respectively (Yoshimine et al. 1998; Sivathayalan and Vaid 2002).

Careful inspection, post-test, confirmed that no root was broken in all of the rooted specimens stress in both the compression and extension tests, implying that the roots had not mobilised their full tensile strength during reinforcement. Indeed, the strain level of concern in the triaxial specimen (up to 5%) was far less than the strain required to break the 1 – 1.5 mm diameter roots (up to 30%); however, 5% axial strain was adequate to identify the failure line of both the bare and rooted specimens (see discussion later), which is important to slope stability design. This highlights that the tensile elastic modulus may be a more relevant root mechanical trait compared to the breakage strength which is advocated in existing root reinforcement models (Wu et al. 1979; Pollen and Simon 2005; Schwarz et al. 2015) to assess the root reinforcement to the soil. Indeed, Bourrier et al. (2013), who investigated the shearing behaviour of rooted soil based on the discrete element method, showed that the amount of root reinforcement to the soil depends on the tensile (or Young's) modulus of the roots.

Upon compression, at low axial strain (i.e. <0.3%), the behaviour of the bare and rooted specimens was apparently the same, both following the strain-hardening response. This implies that any root tensile strength has not yet been mobilised and the response of the soil-root composite was mainly controlled by the soil matrix in this low strain range. After a certain strain level, when phase transformation (shown later

when presenting the associated stress paths) took place, the rooted specimens exhibited more dilation than the bare specimens, hence resulting in higher shear stress for a given strain. Upon extension path, on the other hand, the presence of roots made the quasi-steady-state, as observed in the bare specimen, vanish and made the rooted specimen to exhibit largely strain-hardening behaviour. These highlight that the contribution of the roots to soil reinforcement is anisotropic and depends on the stress path. Indeed, the orientation of the roots in the triaxial specimens was predominantly vertical. Since the root orientation was largely perpendicular to the direction of the major principal stress during triaxial extension, the roots in this case would thus more effectively mobilise their tensile properties to provide shear resistance to the soil.

Root reinforcement effects along compression

Figure 4(b) depicts the compression stress paths exhibited by the bare and rooted specimens. All the bare specimens displayed a slight contraction tendency initially (i.e. reduction of mean effective stress, p') followed by an evident dilation (i.e. increase in p'). The rooted specimens followed a similar stress path, but the magnitude of the initial contraction tendency was larger at higher p' (> 100 kPa). A phase transformation line (PTL) can be identified and the associated friction angle was the same at 28.6° for both the bare and rooted specimens. The stress paths of all the bare specimens eventually converged to a single envelope (failure line FL) with a friction angle of 33.5° , which is consistent with the value found in the literature of Toyoura sand of about 65% RD (Nakata et al. 1998; Kato et al. 2001; Rahman et al. 2014). Similar behaviour was found in the rooted specimens, but the friction angle associated with the FL was only marginally higher (by 2°), while the cohesion was not increased due to the roots.

The experimental observation is similar to the findings reported by Neto and Mahler (2017) who carried out drained triaxial compression tests on tropical cultivated soil with vetiver grass. The effect of the roots on the FL friction angle was small and it is somewhat expected in the present study because (i) the sand matrix of the rooted specimens was intentionally made to have the same RD as the bare specimens; and (ii) the root orientation was predominantly parallel to the direction of the major principal stress upon triaxial compression. The latter means that upon shearing, the roots only marginally mobilised their tensile strength to reinforce the soil. The consistent friction angles obtained from multiple rooted specimens indirectly suggests that the sample

preparation adopted was repeatable. A summary of the shear strength parameters of both the bare and rooted specimens along different stress paths is given in Table 3.

As reported in the literature, Graf et al. (2009) and Foresta et al. (2020) also tested the shear behaviour of cultivated specimens (*Alnus incana* in moraine by Graf et al. (2009) and perennial gramineae grasses in loose pyroclastic soil by Foresta et al. (2020)) subjected to undrained triaxial compression. Both studies found that the presence of roots increased the friction angle significantly by 5° , contrary to the present study (while the root effect on cohesion was almost nil). One major reason for this inconsistency is because of the different root morphologies and distributions being examined in the different studies. Although all these studies focused on grass species, based on the limited information provided, the root diameter was much smaller (yet root length was not reported) and the roots appeared to distributed more uniformly, compared to the present study. Following the state-of-the-art knowledge derived from the studies of fibre-reinforced soil, indeed, the friction angle of sand can be increased noticeably when the fibres are preferably distributed perpendicular to the major principal stress direction, when compared to the case reinforced by fibres which are predominantly parallel to the direction of the major principal stress (Michalowski and Čermák 2002; Diambra et al. 2010; Gao and Zhao 2013; Mandolini et al. 2018).

Root reinforcement effects along extension

Along the extension path (Fig. 4(b)), phase transformation was observed in both the bare and rooted specimens. Differing from the observation in the compression path, the bare specimen was more contractive than the rooted specimen, especially at high effective confining pressure. An instability line (IL) with a friction angle of 26.9° can be identified for the bare specimens, as characterised by a straight line passing through the transient peak shear strength (Lade 1992); this line represents the soil stress state where the deviatoric stress reaches a local and temporary peak, which is associated with the onset of flow liquefaction upon cyclic loading (Murthy et al. 2007).

For the case of rooted specimens, since the behaviour was much more dilative, IL could not be identified. The PTL of the rooted specimen was determined, with a friction angle of 36.8° . At low effective confining pressure (i.e. < 100 kPa), the bare and rooted specimens sheared along the extension path diverged to different FLs. The associated friction angle of the bare and rooted specimens were 41.9° and 51.5° , respectively. Moreover, there was a significant increase in cohesion from 0 kPa (bare

specimen) to 9 kPa after root reinforcement. This is because the roots were predominantly orientated perpendicular to the major principal loading direction upon extension, which mobilised the root tensile properties the most. Indeed, the differences of the intermediate principal stress in the compression and extension stress path can affect the FL friction angle by altering (i) the effective confinement, (ii) anisotropy effects on the dilatancy; and (iii) soil particle rearrangement (Ladd et al. 1977; Corfdir and Sulem 2008; Sadrekarimi and Olson 2011).

Interestingly, at higher effective confining pressure (i.e. > 100 kPa), the bare and rooted specimens converged to the same FL with a friction angle of 41.9° (while cohesion in both cases being zero). With reference to the case of fibre-reinforced soil, some studies Michalowski and Čermák (2002) and Gao and Zhao (2013) showed that the fibre reinforcement increased with an increase in confinement when the confinement was lower than a critical value, beyond which the fibre did not slip in the soil matrix and the failure of the composite was mainly governed by either the fibre yielding or breakage (Michalowski and Čermák 2002; Gao and Zhao 2013). However, Dos Santos et al. (2010) and Kong et al. (2019) showed that the FL of fibre-reinforced soil converged to that of the unreinforced soil in the compression path at high p_c' (i.e. 1000 kPa and 300 kPa, respectively). A similar behaviour was observed in the rooted specimen in the presence study, though the confinement required to converge to the FL of the bare specimen was much lower (i.e. approximately 100 kPa), as compared to the case of the aforementioned fibre studies. A recent study by Li et al. (2017) showed a relationship between peak friction angle and state parameter for fibre-reinforced soil for a range of fibre contents through a series of drained triaxial tests. Unfortunately, this relationship could not be examined for the case of rooted specimens because this study investigated only one RVR in the monotonic test programme and the state parameter cannot be defined (since a critical state was not arrived).

Generally speaking, both plant roots and synthetic fibres reinforce soil by mobilising their interface friction with the surrounding soil and hence their tensile strength and modulus. However, roots and fibres have fundamental differences that make them interact and reinforce the soil rather differently. First of all, roots have lower tensile strength than synthetic fibres and the root tensile strength and modulus are diameter dependent (Boldrin et al. 2017, 2018b). Roots could have been broken during shearing to large strains (Wu et al. 1979; Schwarz et al. 2013). The tensile properties

of fibres, on the other hand, are independent of diameter. Secondly, a natural root system is composed of interconnected roots of a wide range of diameters (hence mechanical properties), whereas fibres are individual and they have relatively more uniform aspect ratio. Lastly, root distribution depends primarily on plant characteristics (e.g. deep rooted for vetiver grass) and habitat (soil and environment), whereas fibre distribution depends on sample preparation method (e.g. predominant fibre orientation parallel to soil bedding plane by compaction (Michalowski and Čermák 2002; Soriano et al. 2017). Given these major differences, understanding how roots affect shearing behaviour including dilatancy and anisotropy differently from fibres and how these differences are interpreted in a critical-state framework are complex. More testing aided by, for example, microscopic investigation is needed to better understand the soil-root mechanical interaction in the future.

The triaxial test results showed that the mechanical effects of root reinforcement on the soil were stress path-dependent. Plant roots did not necessarily cause an increase in soil cohesion (i.e. root cohesion) and introduced little or no effect on the soil friction angle, as revealed from the extensive direct-shear test data in the existing soil bioengineering literature. Although the findings obtained from the direct-shear tests are applicable to the soil elements sheared in the direction parallel to the slope surface (see Fig. 1), they may not apply to the soil elements located near the slope crest and slope toe. For deep-rooted species such as vetiver, planting them near the slope toe would seem to be an effective way for slope stabilisation because, following the extension test results (Fig. 4), the roots could introduce a remarkable increase in the soil friction angle by almost 10° . Near the slope crest, on the other hand, planting the same kind of deep-rooted species would be much less effective. However, based on the triaxial test results, any laterally-rooted plant species may be a better alternative since the direction of root growth in this case would be predominantly perpendicular to the shearing direction and plants with this root distribution might favour the mobilisation of root tensile strength for more effective soil reinforcement.

Cyclic behaviour

Figure 5 shows the cyclic stress-axial strain curves of the bare and rooted specimens of the three different RVRs (0.23%, 0.45% and 0.67%) tested at the CSR of 0.2 and p_c' of 100 kPa. It is evident that the bare specimen (Fig. 5(a)) exhibited a flow failure with limited deformation (also known as limited flow failure) in the extension part of

the cyclic loading; this corresponds to the quasi-steady state condition identified in the monotonic extension test, at which there was a slight reduction of deviatoric stress accompanied with a remarkable strain (refer to Fig. 4(a)). This kind of cyclic failure mode of sand has been reported extensively in the literature (e.g. Asadi et al. 2018; Ishihara 1993; Koseki et al. 2005). For rooted specimens, irrespective of RVRs, cyclic mobility was the prevailing failure mechanism (Figs 5(b), (c) and (d)). These test results indicate that the presence of roots may prevent the sand from undergoing of catastrophic flow failure mechanism upon seismic loading, such as in an earthquake.

To investigate the limited flow failure mechanism of the bare specimen in greater detail, the effective stress paths of the two bare specimens that were tested under the same void ratio and p_c' of 100kPa in the monotonic compression and cyclic loading condition at the CSR of 0.3 are depicted in Fig. 6. The cyclic stress path during the first cycle closely followed the monotonic stress path before arriving at the first reversal loading point (point 1; Fig. 6(a)). The specimen then exhibited instability when the stress state reached the IL in the extension space (i.e. point 2), which corresponded to the transient peak condition and trigger point of softening in the extension monotonic loading; known as flow liquefaction with limited deformation (Ishihara 1993). As instability occurred beyond point 2, the specimen displayed significant increases in axial strain (point 2; Fig. 6(b)) and pore-water pressure ratio (r_u , defined as the ratio of pore-water pressure to p_c') point 2; Fig. 6(c)). When the loading direction reversed (point 3; Fig. 6(a)) and the stress state reached the extension PTL (i.e. point 4), both the axial strain and r_u remained approximately constant. This kind of soil response might be referred to as hybrid behaviour; the soil exhibited the limited flow liquefaction that possessed some characteristics of both cyclic instability and cyclic mobility. In other words, it was a combination of both the contractive and dilative responses of soil (Baki et al. 2019). Beyond point 4 in Fig. 6(a), the dilative tendency of the soil was suppressed, and the contractive tendency prevailed as indicated by the significant build-up of the pore-water pressure as shown in Fig. 6(c). As r_u approached one, initial liquefaction occurred, accompanied with the development of large strain (point 5). At point 6 in Fig. 6(a), the specimen started to deliquefy and this stress state coincided with the compression PTL. As the soil tended to dilate (as indicated by the reduction of pore-water pressure ratio) and following the cyclic mobility phenomenon, the stress path followed the compression FL until the next reversal loading point. At the compression PTL (point 7), the r_u increased

remarkably, and the soil was contractive. Beyond point 7, the r_u approached one and the liquefaction again occurred, indicated by the development of large strains.

Figure 7(a) shows the effective stress path of the two rooted specimens (RVR of 0.45%) that were tested under the same void ratio and p_c' of 100 kPa in the monotonic compression and cyclic loading condition at the CSR of 0.3. The first cycle of the stress path closely followed the monotonic compression path until the first reversal loading point (point 1). While there was no significant increase in the axial strain at point 1 (Fig. 7(b)), the peak r_u of the rooted soil in the compression side of the first cycle of loading (Fig. 6(c)) was 1.5 times higher than that of the bare specimen (refer to point 1 in Fig. 5(c)). This means that the rooted specimen was more contractive along the compression part of the cyclic loading. In contrast, along the extension part of the first cycle of loading, the peak r_u of the rooted specimen was 1.45 times lower than the bare specimen. This suggests that the roots made the soil more dilative and had greater ability to resist liquefaction compared to the root effects displayed in the compression part of the cyclic loading. These observations are consistent with the results of the monotonic tests where the roots contributed more to soil reinforcement along the extension path (refer to Fig. 4).

The axial strain and r_u near the compression and extension PTLs were marked in points 2, 4, 5, 6 in Figs 7(b) and (c), respectively. The fact that r_u did not build up abruptly but increased gradually in the first few loading cycles suggests that the presence of roots with the RVR of 0.45% prevented the specimen from experiencing the flow failure mechanism. After the initial liquefaction at point 7 (i.e. r_u higher than 0.9) in Fig. 7(c), the cyclic stress path moved along both the compression and extension FLs; this indicates that the rooted specimen followed a cyclic mobility (Castro and Poulos 1977) rather than the limited flow failure exhibited by the bare specimen.

In the literature, fibres have been demonstrated to increase the liquefaction resistance of sand (Krishnaswamy and Thomas Isaac 1994; Noorzad and Fardad Amini 2014; Chegenizadeh et al. 2018). However, the switch of the liquefaction failure mechanism (e.g. from flow failure to cyclic mobility as observed in the present study) due to the addition of fibres was not found. Indeed, in most of these existing studies of fibre-reinforced sand, moist or vibrant tamping method was used to produce the samples, which generally yielded isotropic samples (Li et al. 2018). As a result, the cyclic mobility without any flow failure was observed, even in bare specimens. In the

present study, both the bare and rooted specimens were produced by the dry deposition method, which could closely simulate fabric anisotropy (Miura and Toki 1982; Vaid et al. 1999). This explains why flow failure with limited deformation occurred in all of the bare specimens tested at different CSRs in the extension part of the cyclic loading. In this part of loading, because of the preferential orientation of the particles with respect to the major principal stress direction, the bare specimen was contractive and was vulnerable to flow failure (Sivathayalan and Vaid 2002; Sadrekarimi 2016). Since the root orientation was predominantly perpendicular to the direction of the major principal stress of the triaxial specimen, a considerable portion of loading, in the extension phase, was transferred to the roots, which mobilised their tensile strength and stiffness to not only increase the soil effective stress but also to reduce the soil shear stress in order to prevent flow failure from taking place in the rooted specimens.

Mechanisms of liquefaction

Figure 8 shows the relationships of r_u (Fig. 8(a)) and DA_{ε_a} (Fig. 8(b)) with the number of loading cycles (normalised by the respective value at failure) of the soil specimens with different RVRs and CSRs. Consistent with the observed undrained cyclic responses of Toyoura sand reported in the literature (Ishihara 1993; Koseki et al. 2005), both the r_u and DA_{ε_a} of the bare specimen increased significantly, when it started to develop the limited flow failure mechanism as the r_u approached approximately 0.5 to 0.6. In contrast, the behaviour of the rooted specimens, irrespective of the magnitudes of CSR and RVR, was remarkably different; even though the r_u reached 1.0 at a small number of loading cycle, the DA_{ε_a} increased only gradually, and the rooted specimens remained stable. This implies that r_u could not be used as an indicator of the initiation of liquefaction for root-reinforced soil. This is similar to the findings from a recent study of fibre-reinforced soil reported by Zhang and Russell (2020), who also discovered that the reinforced specimens did not liquefy even r_u has approached one. A plausible explanation for this inconsistent phenomenon (between the bare and root- or fibre-reinforced specimens) is due to the root- or fibre-induced changes in the soil effective stress as a result of the load redistribution between the roots (or fibres) and soil particles which primarily depends on the relative direction between the root (fibre) orientation and the principal stresses.

Based on the effective stress concept of fibre-reinforced soil proposed by Ibraim et al. (2010), Zhang and Russell (2020) derived a direction-dependent equation for r_u and the prediction of the liquefaction occurrence can be improved by incorporating the fibre effects in the effective stress of soil.

The relationships between r_u and the average shear strain γ are depicted in Fig. 9, where γ is equal to 1.5 times the axial strain. Interestingly, a unique relationship exists for the bare specimens, irrespective of the CSRs. This unique γ - r_u relationship may be described by an empirical equation by Chen et al. (2020) for rooted and bare specimens in the present study:

$$\gamma = A \tan\left(\frac{\pi}{2} r_u\right) \quad (2)$$

where A is a material constant. Based on the experimental data of the present study, A is equal to 0.16 by best-fitting. This value of A is smaller than that (0.25) reported by Chen et al. (2020), probably because they studied the liquefaction potential of silty soil with low plasticity (plasticity index = 3) using a torsional shear apparatus which was inherently different from the bare and root-reinforced sand subjected to the cyclic triaxial stress path in the present study. It can be seen that most of the data from the rooted specimens fell on the same trend, implying that the variation of γ with r_u is not affected by the roots. Indeed, Cetin and Bilge (2012) and Dobry and Abdoun (2015) suggested that r_u has a unique relationship with γ as r_u resulted from the change in soil structure upon shear distortion, regardless to the amounts of CSR and RVR.

Root effects on liquefaction resistance

To quantify the effects of the roots, or RVRs, on the liquefaction resistance of the soil at failure, Fig. 10 shows the number of loading cycles to failure (when DA_{ε_a} of 5% was reached) with CSRs (0.2, 0.25, 0.3) for the soil specimens of different RVRs (0%, 0.23%, 0.45%, 0.67%). As expected, the bare specimens took a larger number of loading cycles to reach failure when the CSR was reduced (Fig. 10(a)). The same trend can be observed for all the rooted specimens. For any given CSR, the number of loading cycle required to fail a rooted specimen that has a higher RVR was larger, suggesting that the presence of roots improved the soil resistance to liquefaction. It appears that the roots were more effective in enhancing the liquefaction resistance at

higher CSR, as indicated by the greater percentage increase in the number of loading cycles required to reach the failure.

To further investigate the significance of the root reinforcement, the number of loading cycles required to fail the rooted specimen (N_L) was normalised by that of the bare specimen ($N_{L,B}$), and this normalised value is seen to be related with RVR in Fig. 10(b). Interestingly, the relationship for low CSR of 0.2 is approximately linear, but that for higher CSRs the relationship is exponential. The improvement of liquefaction resistance is likely attributed to the root-induced increases in both cohesion and friction angle in the extension phase of the cyclic loading. For the cases of fibre-reinforced soil, it is a common observation from the literature that the liquefaction resistance increases with an increase in the fibre content (Chegenizadeh et al. 2018; Noorzad and Fardad Amini 2014; Ye et al. 2017), consistent with what is found in the present study for the root-reinforced soil. However, Ye et al. (2017) reported that the contribution of the fibres to soil reinforcement was more remarkable at lower CSRs, unlike the rooted case where the reinforcement was more significant at high CSRs (Fig. 10(a)). This difference may be because of the use of different failure criteria of liquefaction between the two studies; Ye et al. (2017) defined failure as r_u approached unity, whereas the present study used DA axial strain of 5%.

Summary and conclusions

A comprehensive triaxial test campaign was undertaken to investigate the effects of plant roots on the monotonic and cyclic behaviour of soil subjected to different stress paths under undrained condition. The increases in the soil shear strength properties and liquefaction resistance due to the presence of roots have been quantified and the underlying mechanisms of root reinforcement were investigated. The key conclusions of this study may be drawn as follows:

- a) When tested under the triaxial condition, roots can increase the soil friction angle, unlike most of the results reported in existing direct-shear tests where the friction angle was largely unchanged.
- b) The root reinforcement effect is anisotropic because the root-induced change in soil friction angle is found to be path-dependent. While the friction angle change is minimal upon compression, the friction angle upon extension increased significantly by about 10° (from 41.9° (bare specimen) to 51.5° (rooted specimen) at low confining pressure of <100 kPa. This can be explained by the relative

direction between the root orientation (which is predominantly vertical in this study) and the direction of major principal stress. Upon extension, these two directions are perpendicular to each other, and the roots likely mobilised their tensile properties (more than that upon compression) to provide greater soil reinforcement.

- c) Along the extension path, the presence of the roots changed the stress-strain behaviour from strain-softening (in the case of bare soil) to hardening. Compared to the compression path, the rooted specimens displayed more significant dilative behaviour upon extension due to the greater mobilisation of root reinforcement.
- d) An engineering implication of the monotonic test results is that deep-rooted plant species such as the vetiver grass should be strategically grown near the slope toe, where the soil along a slip surface is normally subjected to extension, so that the root tensile properties, hence the reinforcement effects, can be mobilised the most, when compared to growing in other positions of the slip.
- e) Roots can effectively increase the liquefaction resistance, primarily because of the mobilisation of root tensile properties during the extension part of cyclic loading. The presence of roots changed the failure mechanism from limited flow (in the case of bare soil) to cyclic mobility.
- f) Although pore-water pressure ratio can be used to indicate the occurrence of the liquefaction of bare soil (when reaching 1.0), it does not apply to root-reinforced soil. When the roots were present, the double-amplitude axial strain continued to increase, even the pore-water pressure ratio has reached 1.0.
- g) The improvement of liquefaction resistance increased with an increase in RVR, and this improvement is a function of CSR; that is, the higher the CSR, the greater the root reinforcement effects would be. The liquefaction resistance (measured by the number of loading cycles required to reach failure) has an approximately linear relationship with RVR at low CSR, but the relationship became exponential when CSR exceeded 0.2.

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List of symbols

A	material constant
CSR	cyclic stress ratio
C_c	coefficient of curvature
C_u	coefficient of uniformity
c'	effective cohesion
D_{10}	particle diameter of 10% passing
D_{30}	particle diameter of 30% passing
D_{50}	particle diameter of 50% passing
D_{60}	particle diameter of 60% passing
DA_{ε_a}	double amplitude axial strain
e	void ratio
e_{min}	minimum void ratio
e_{max}	maximum void ratio
G_s	specific gravity
p'	mean effective stress
p_c'	effective confining pressure
q	deviatoric stress
q_{cyc}	cyclic deviatoric stress
RVR	root volume ratio
r_u	excess pore water pressure ratio
ε_a	axial strain
γ	shear strain
σ'_{3c}	minor effective principal stress
ϕ'	friction angle

Table 1. Index properties of Toyoura sand

Index properties	Value
Specific gravity, G_s [-]	2.65
Maximum void ratio, e_{max} [-]	0.977
Minimum void ratio, e_{min} [-]	0.597
Particle diameter of 10% passing, D_{10} [mm]	0.17
Particle diameter of 30% passing, D_{30} [mm]	0.19
Particle diameter of 50% passing, D_{50} [mm]	0.22
Particle diameter of 60% passing, D_{60} [mm]	0.23
Coefficient of uniformity, C_u [-]	0.92
Coefficient of curvature, C_c [-]	1.35

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Table 2. Summary of test program

Test	Sample type	RVR (%)	Stress path	p_c' (kPa)	e	CSR
CB15	Bare	0	Compression	15	0.733	N.A
CR15	Rooted	0.45		15	0.741	
CB30	Bare	0		30	0.732	
CR30	Rooted	0.45		30	0.740	
CB100	Bare	0		100	0.725	
CR100	Rooted	0.45		100	0.732	
CB200	Bare	0		200	0.719	
CR200	Rooted	0.45		200	0.727	
EB15	Bare	0	Extension	15	0.733	N.A
ER15	Rooted	0.45		15	0.741	
EB30	Bare	0		30	0.732	
ER30	Rooted	0.45		30	0.739	
EB100	Bare	0		100	0.726	
ER100	Rooted	0.45		100	0.733	
EB200	Bare	0		200	0.718	
ER200	Rooted	0.45		200	0.729	
B- CSR 0.2	Bare	0	Cyclic	100	0.726	0.2
RL- CSR 0.2	Rooted	0.23		100	0.733	0.2
RM- CSR 0.2	Rooted	0.45		100	0.735	0.2
RH- CSR 0.2	Rooted	0.67		100	0.740	0.2
B- CSR 0.25	Bare	0		100	0.727	0.25
RL- CSR 0.25	Rooted	0.23		100	0.731	0.25
RM- CSR 0.25	Rooted	0.45		100	0.734	0.25
RH- CSR 0.25	Rooted	0.67		100	0.739	0.25
B- CSR 0.3	Bare	0		100	0.729	0.3
RL- CSR 0.3	Rooted	0.23		100	0.732	0.3
RM- CSR 0.3	Rooted	0.45		100	0.735	0.3
RH- CSR 0.3	Rooted	0.67		100	0.740	0.3

Note: p_c' is effective confining pressure; e is void ratio of the sand-root composite after consolidation; CSR is cyclic stress ratio

Table 3. Summary of the shear strength parameters of the bare and rooted specimens subjected to monotonic loading

Envelope	Sample type	RVR (%)	ϕ' (deg)	c' (kPa)
<i>Compression stress path</i>				
Failure line	Bare	0	33.5	0
Failure line	Rooted	0	35.5	0
Phase transformation line	Bare, rooted	0, 0.45	28.6	0
Instability line	Bare, rooted	0, 0.45	NA	NA
<i>Extension stress path</i>				
Failure line	Bare	0	41.9	0
Phase transformation line	Bare	0	37.5	0
Instability line	Bare	0	26.9	0
Failure line ($p_c' < 100$ kPa)	Rooted	0.45	51.5	8.9
Failure line ($p_c' > 100$ kPa)	Rooted	0.45	41.9	0
Phase transformation line	Rooted	0.45	36.8	0
Instability line	Rooted	0.45	NA	NA

Fig. 1. Rotation of major and minor principal stresses along a failure slip surface with respect to the root orientation

Fig. 2. Preparation of vetiver roots: (a) scanned roots for measuring root traits; and (b) roots in a triaxial mould ready for subsequent dry deposition of sand

Fig. 3. Results of repeated undrained compression tests of rooted specimens with a RVR of 0.45% at p'_c of 100 and 200 kPa: (a) deviatoric stress-axial strain curve; and (b) excess pore-water pressure (EPWP)-axial strain curve

Fig. 4. Undrained compression and extension tests on the bare and rooted specimens (with RVR of 0.45%) at p_c' of 15, 30, 100 and 200 kPa: (a) deviatoric stress (q)-axial strain (ϵ_a) curves; and (b) effective stress paths

Fig. 5. Typical cyclic responses of the bare and rooted specimens tested at the same CSR of 0.2 but different RVR (a) 0% (i.e. bare specimen); (b) 0.23%; (c) 0.45%; and (d) 0.67%

Fig. 6. Interpretation of limited flow failure mechanism of the bare specimen tested at $CSR=0.3$: (a) effective stress path; (b) relationship of axial strain (ϵ_a) and the number of loading cycles; and (c) relationship of pore-water pressure ratio (r_u) with the number of loading cycles

Fig. 7. Interpretation of cyclic mobility, using the behaviour of rooted specimen (RVR= 0.45%) tested at CSR=0.3: (a) effective stress path; (b) relationship of axial strain (ϵ_a) and number of cycles; and (c) relationship of pore-water pressure ratio (r_u) with number of cycles

Fig. 8. Relationships of (a) pore-water pressure ratio (r_u) and (b) double-amplitude (DA) axial strain with normalised loading cycle at different CSRs and RVRs. Note the results from the specimen B-CSR0.3 and RL-CSR0.3 are not shown in Fig. 8(a) because the number of loading cycle required to reach liquefaction was less than 2, which is not possible to be presented in the curve.

Fig. 9. Relationships between γ and r_u at different CSRs and RVRs

(a)

(b)

Fig. 10. Relationships between (a) cyclic stress ratio (CSR) and number of loading cycles to failure defined at an $\varepsilon_a = 5\%$ (N_L) for the triaxial specimens of different RVRs; and (b) the ratio of loading cycle and RVR at different CSRs