Evaluation of mechanical properties of sand with internal pipe by torsional shear tests

Yang Yangⁱ⁾ and Reiko Kuwanoⁱⁱ⁾

i) Ph.D Student, Department of Civil Engineering, the University of Tokyo, 4-6-1 Komaba, Meguro-Ku, Tokyo 153-8505, Japan.

ii) Professor, Institute of Industrial Science, the University of Tokyo, 4-6-1 Komaba, Meguro-Ku, Tokyo 153-8505, Japan.

ABSTRACT

Landslides due to piping have occurred frequently in rainy season recently. Piping, known as a complex phenomenon of internal erosion, has not been quantitatively studied in laboratory by element experiment. As an attempt to achieve piping effect, artificial pipes both in vertical and horizontal were created by dissolving glucose in Toyoura sand. A series of hollow cylindrical torsional shear tests were conducted for specimens with and without pipes under different confining pressure. Strains during piping propagation were measured locally by clip gauges. Small strain stiffness of sand was investigated by applying small torsional cyclic loading under different principal stress directions. In addition, failure behavior of sand subjected to piping effect was studied. It was observed that shear band propagated partially along the piping plane in specimen with horizontal pipe.

Keywords: piping, shear modulus, torsional cyclic loading, anisotropy, shear band

1 INTRODUCTION

Internal erosion of soil resulted from piping, seepage or overtopping is the main cause of hydraulic structure failures. Recently, landslides due to piping have also drawn much attention among geotechnical engineers. For the landslides both in Izuoshima (Oct. 2013) and Hiroshima (Aug. 2014), piping holes along the slope were observed and considered as one important reason for the hazard which caused severe casualties (Masaaki, 2014).

Piping occurs when water flows through a cavity, crack or other continuous void within the soil. Compared with surface erosion, such internal erosion is harder to quantify for the reason that only subtle evidence could be observed externally even when severe migration of soil particles has already taken place. Despite the rich research on piping phenomena through model tests (Wan et al., 2004; Bonelli et al., 2006), there is little element experiments conducted on the soil subjected to piping effect.

It has been identified by many researchers that concentrated leaks loosens the soil structure and reduces the soil's shear strength. Since the elastic properties of soils play an important part in deformation prediction of ground, knowledge of piping effect on small strain stiffness of sandy soil should be clarified. In addition, it has been known that soils formed under gravity are anisotropic in terms of strength and stiffness. Such anisotropy could be divided into the inherent anisotropy (Arthur and Menzies, 1972) and induced anisotropy (Wong and Arthur, 1985). Piping, acting as

a weak plane, induces another anisotropy in soil structure, which would have significant influence on the failure behaviour of soil. Previous laboratory study on shear band formation has focused on the anisotropy caused by bedding plane or rotation of principal stress (Tatsuoka et al., 1990; Han et al., 1993; Yoshida et al., 1994). However, there is little research about piping-induced anisotropy.

Piping is a sophisticated phenomenon as it deals with reformed soil particles with unpredictable structure. In this study, piping effect was successfully generated by dissolving pipe shape glucose powder in specimen. Quasi-elastic properties of soil subjected to piping effect at very small strain level were evaluated by conducting a series of hollow cylindrical torsional shear tests on dense Toyoura sand.

2 HOLLOW CYLINDRICAL TORSIONAL SHEAR TEST

In this study, a high-capacity torsional shear test apparatus developed at the Institute of Industrial Science, University of Tokyo was employed.

2.1 Apparatus

The apparatus mainly consists of a cell, loading system and measurement devices. The loading system consists of an AC servo-motor, a reduction gear system with two gears, electronic magnetic clutches and brakes. These loading devices can be controlled automatically by a computer. The vertical load F and torque T were applied on the hollow cylindrical specimen

simultaneously and independently by two servo-motors and measured through a two-component load cell (① in Fig.1). Cell pressure is applied through an electro-pneumatic transducer (E/P) with a capacity of 1000 kPa, and measured by high capacity differential pressure transducer (HCDPT). Low capacity differential pressure transducer (LCDPT) is used to measure the volume change of inner hollow, which is fully filled with de-airing water, by the difference in water heads between two burettes with one collecting water from inner hollow and the other as a reference. Throughout the tests, the cell and LCDPT are connected by a stiff nylon tube. By this way, inner and outer cell pressures are equal to each other, and the radial stress σ_r is equal to the circumferential stress σ_θ .

Fig. 1. Hollow cylindrical specimen and transducers.

2.2 Material

Toyoura sand (batch J) was used in this study, which is uniformly graded sand with sub-angular particles (specific gravity $G_s = 2.640$, the maximum void ratios $e_{max} = 0.992$, the minimum void ratios $e_{min} = 0.678$). Hollow cylindrical specimen with outer diameter of 10 cm, inner diameter of 6 cm and height of 10 cm were prepared by air-pluviation method.

The concept of using water soluble material to create loosened sand was examined by sugar, salt and glucose (Renuka et al. 2011). In this study, both vertical and horizontal pipes were created with glucose powder. For vertical glucose pipe, a plastic straw of 4.5 mm in diameter was placed in advance. Glucose powder was filled into the straw after completing the sand pluviation, and then the straw was removed, with the glucose left inside the specimen. The horizontal pipe was casted by compacting glucose paste which was made by mixing the powder with nearly 5% of water in

a hollow steel pipe with 5.5 mm in diameter. After that, the pipe was cut by 1 cm and placed at mid-height of specimen in a circle during pouring of sand (Fig.2).

Fig. 2. Specimen with internal glucose pipe.

2.3 Test procedures

Specimen was first subjected to isotropic consolidation. After around 16 hours dissipating the creep effect, small torsional cyclic loading, with peak to peak stress amplitude of 4 kPa, was applied in order to obtain the shear modulus G of dry sand. Then 1300 ml of de-aired water was infiltrated from bottom pedestal and at a rate of 12-16 ml/min to completely dissolve the glucose pipe, and came out from top cap. The second small torsional cyclic loading was applied after 15 hours to examine the variation of G of sand subjected to piping effect. Before τ was applied, axial stress σ_z was increased to a certain value. Again at several stable stress of τ , followed by a creep period of about 10 minutes, torsional cyclic loadings were conducted, corresponding to different α . After α reached 30° , all the specimens were monotonically sheared at a strain rate of 0.08%/min under drained conditions. Stress path is shown in Fig.3. Test conditions for each specimen are summarized in Table.1.

Fig. 3. Stress path during cyclic loadings.

Table 1. Test conditions.

Test ID	D_{rini} (%)	e_{ini}	Pipe number	Pipe direction	σ'_{zini} (kPa)	σ'_z (kPa)
Case 1	71.2	0.720	0	-	30	60
Case 2	75.6	0.703	4	Vertical	30	60
Case 3	77.8	0.695	1	Horizontal	30	60
Case 4	76.5	0.700	0	-	50	80
Case 5	77.0	0.698	4	Vertical	50	80
Case 6	74.1	0.709	1	Horizontal	50	80

3 STRESSES AND STRAINS IN TORSIONAL SHEAR

Four stress components on the specimen in hollow cylinder torsional shear apparatus, namely axial stress (σ_z), radial stress (σ_r), circumferential stress (σ_θ) and shear stress ($\tau_{z\theta}$) can be defined by controlling the vertical axial load (F_z), the torque (T), outer cell pressure (p_o) and the inner cell pressure (p_i). The relationship among the above stress and loading components are defined as follows (Hight et al., 1983):

$$\sigma_z = \frac{F_z}{\pi(r_o^2 - r_i^2)} + \frac{(p_o r_o^2 - p_i r_i^2)}{(r_o^2 - r_i^2)} \quad (1)$$

$$\sigma_r = \frac{(p_o r_o + p_i r_i)}{(r_o + r)} \quad (2)$$

$$\sigma_\theta = \frac{(p_o r_o - p_i r_i)}{(r_o - r)} \quad (3)$$

$$\tau_{z\theta} = \frac{3T}{2\pi(r_o^3 - r_i^3)} \quad (4)$$

where r_o and r_i are the outer and inner radius of the specimen.

In order to measure changes in the outer diameter of specimen, three clip gauges were fixed outside the membrane with the support of aluminum blocks. Arrangement of sensors is shown in Fig. 4.

Fig. 4. Arrangement of clip gauges.

In order to calculate the radial strain ϵ_r and circumferential strain ϵ_θ , two assumptions were made: i) the specimen remained right cylinder for the inner hollow, and ii) the sand influenced by piping effect is 1/4 of the total volume for vertical-pipe-specimen and 1/5 for horizontal-pipe-specimen.

The external displacement transducer was employed to measure the average axial strain, and two potentiometers were used to measure the rotation angle of the specimen during shear. In addition, one pair of gap sensors with capacity of 4mm were used to measure the rotational displacements of the top cap during small torsional cyclic loading, by which the shear modulus could be obtained. Fig. 5 presents an example of computation of $G_{z\theta}$.

Fig. 5. Evaluation of $G_{z\theta}$ measured by gap sensors from the 10th cycle out of 11 during isotropic consolidation in Case 1.

4 RESULTS AND DISCUSSIONS

4.1 Volumetric strain

Piping effect is a sophisticated phenomenon as it deals with reformed soil particles with unpredictable structure. Such kind of piping effect has not been quantitatively evaluated yet. In this study, as an attempt to achieve this objective, deformation of loosened sand by means of dissolving glucose was observed during the propagation and expansion of piping by clip gauges.

Fig. 6 showed the radial strain variation during the isotropic consolidation and water infiltration of specimens with pipes under confining pressure of 50kPa. For all of three clip gauges, similar strain increments during isotropic stress increased from 30kPa to 50kPa was observed, which were around 0.254% for vertical-pipe-specimen and 0.279% for horizontal-pipe-specimen. Another obvious increment was found when water was filled in, indicating the formation of piping. For specimen with 4 vertical pipes, where three clip gauges were attached near the glucose, similar shrinkage along the height of specimen appeared as shown in Fig. 6(a). On the other hand, for specimen with horizontal pipe at the mid-height where clip gauge 3 was fixed on, large non-uniform deformation was observed (Fig. 6(b)). Here “VP” and “HP” stand for vertical pipe and horizontal pipe respectively, while NP represents no-pipe-specimen.

Fig. 6. Variation of radial strains before shear

Fig. 7. Variation of volumetric strains before shear

Volumetric strain variation among all test cases is shown in Fig. 7. It should be noted that the volume proportion of glucose to the total specimen is about 1.27 % for four vertical glucose pipes and 1.17 % for horizontal glucose pipe. During water infiltration, slightly larger volumetric strain increments were observed for specimen under lower confining pressure (30 kPa) in comparison with those under larger confining pressure (50 kPa). When comparing the data with the initial glucose volume, it could be inferred that piping was successfully generated in sand, in other words, voids more than 60% of the original volume of glucose were left in the specimen. Still, it should be noticed that some compression was induced due to the increasing of σ_z before shear stress was applied.

4.2 Shear modulus $G_{z\theta}$

In order to evaluate the elastic properties of Toyoura sand, small torsional loading were conducted at different stress states, including the rotation of principal stress at the initial shearing period. The angle of the major principal stress σ_1 relative to the vertical direction is defined as α , which can be computed by Eqs. (5).

$$\tan 2\alpha = \frac{2\tau}{(\sigma_z - \sigma_\theta)} \quad (5)$$

Since deviator stress was kept 30 kPa for all the cases after water infiltration, the same value of α could be achieved under the same value of τ during shearing. Therefore, the effect of principal stress rotation could be clearly identified. The influence of intermediate principal stress parameter b , which changes simultaneously with α ($b = \sin^2 \alpha$) due to the same inner and outer cell pressure, is not discussed in this paper.

Shear modulus $G_{z\theta}$ measured by gap sensors were normalized by void ratio function $f(e) = (2.17 - e)^2 / (1 + e)$ (Hardin and Richart, 1963) in order to eliminate the effect of void ratios among different specimens. Fig. 8 shows the $G_{z\theta}/f(e)$ values during the isotropic consolidation, after piping formation, increase of axial stress σ_z , and the rotation of major principal stress σ_1 .

Fig. 8. Variation of shear modulus.

Fig. 9. Reduction rate of G_{z0} .

Degradation of G_{z0} was observed after water infiltration for all the specimens as shown in Fig. 8. Plotting the reduction rate relative to the G_{z0} at initial dry state (Fig. 9), rather close value around 0.87 was found for specimens with pipes, indicating that such degradation of G_{z0} might be independent of pipe direction.

Increment of G_{z0} was observed after σ_z increased, from which the dependency of G with $(\sigma_z \sigma_\theta)^{0.5n}$ (Nguyen, H. and Koseki, J., 2005) was considered to be the reason why larger growth shown in Fig. 7(a) where σ_z was increased from 30 kPa to 60 kPa.

Under torsional shearing when α rotated, degradation of G_{z0} was observed for all the specimens. A Larger reduction appeared when α reached 30° , especially for specimens under lower confining pressure. The reason might lies in the angle of internal friction ϕ , which increased simultaneously with τ , and exceeded 30° in the first three cases during the last cyclic loading. Further investigations are required to verify the influence of ϕ on shear modulus.

It should also be noted that the stresses were not uniform across the wall of hollow cylinder specimen. However, such non-uniformity was not considered in this study for the fact that the specimen itself was not homogenous and disturbed due to the existence of piping effect.

4.3 Shear strength

Followed by the last small torsional cyclic loading under τ equaled 26 kPa, monotonic shear was conducted at a strain rate of 0.08%/min under drained conditions, while the normal stresses were kept constant. Shear strain was obtained from the average results of two potentiometers.

Fig.10 shows the relationship between shear strain and stress as well as major principal stress angle. Reduction of peak shear strength could be found for sand subjected to piping effect. For all the specimens, the major part of principal stress rotation took place at the very early stage of shearing where γ was less than 1%, and residual state was reached at shear strain about 15%. σ_1 direction at the peak state was in the range of $35^\circ \sim 40^\circ$ from vertical, and this value was slightly smaller for specimen with pipe.

Fig. 10(a). Relationship among τ , γ and α during shearing

Fig. 10(b). Relationship among τ , γ and α during shearing

Generally, shear bands appear at intermediate directions between zero-extension direction and maximum stress ratio plane. The peak mobilized angle of internal friction ϕ_{peak} for the Toyoura sand in this research was confirmed to be around 40° from the previous triaxial compression tests conducted under similar density (Yang, Y., Kuwano, R. 2014). Therefore, the direction of shear band θ was expected to be $50^\circ \sim 65^\circ$ relative to the direction of σ_3 (Fig.11). Due to the restriction of the rigid top and bottom pedestals, only a single shear band was developed freely. However, for horizontal-pipe-specimen, where the bedding plane of air-pluviated Toyoura sand coincided with piping direction, shear band which partially developing along the pipe was observed.

Fig. 11. Sketch of shear band.

Fig.12 shows the shear band in specimen with horizontal pipe from the backside and front side. The angle between pipe plane (horizontal) and shear band was measured to be around 25° , which coincides with the previous analysis.

Fig. 12. Shear band in specimen with horizontal pipe.

5 CONCLUSIONS

In this research, mechanical properties of loosened soil subjected to piping effect were studied through a series of torsional shear tests by dissolving glucose pipes in Toyoura sand. Followings are the conclusions obtained from the present study.

- 1) Larger volumetric strains were observed in specimen with internal pipes under lower confining pressure

during piping formation at isotropic stress state.

- 2) Reduction of shear modulus caused by piping effect showed more dependency on the volume of influenced area compared with the piping direction.
- 3) Degradation of $G_{z\theta}$ was observed during the rotation of principal stress for all the specimens under constant normal stress. A larger decrease of $G_{z\theta}$ was found when α reached 30° .
- 4) Specimen subjected to piping effect showed lower resistance against shear, especially for horizontal-pipe-specimen, where shear band developed partially along pipe plane due to the non-uniform stress distribution by piping effect.

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