EFFECT OF SPECIMEN SIZE ON BEHAVIOUR OF DENSE SAND IN LARGE STRAIN TORSIONAL SHEAR APPARATUS

Muhammad UMAR[1], Takashi KIYOTA[2] and Gabriele CHIARO[3]

ABSTRACT: In this study, an effort has been made to study the influence of specimen size on deformation characteristic of medium dense (Dr 40-50%) Toyoura sand subjected to undrained cyclic loading. Two series of test were performed on hollow cylindrical specimens with different size, by air pluviation method, isotropically consolidated at an effective stress of 100kPa and then cyclically sheared under undrained conditions. Test were performed by using a modified torsional shear apparatus that is capable of achieving double amplitude shear strain up to about 100%. A parabolic relation is establish for the membrane correction force taking into account specimen size affect. In addition, comparison of liquefaction resistance, which is evaluated at double amplitude shear strain (γ_{DA}) of 7.5%, is provided. Furthermore, the limiting value of the shear strain, at which initiation of strain localization appear during undrained shear loading test is evaluated by comparing the deviator stress (q) with shear strain(γ).

Key Words: Specimen size effect, advance torsional shear, cyclic undrained

INTRODUCTION

Specimen size has been investigated by various researchers on the behavior of granular soils using triaxial shear tests (marshal 1967, Marachi et al. 1969, Chew and Bharati 2011, Tarek et al (2014)). Shear strength parameters are significantly influenced by the change in the specimen size, that can affect the design and analysis of many geotechnical applications. Particularly, difference in the instability lines can affect in evaluating the liquefaction trigger resistance of soils. Critical state models (Jefferies 1993; Manzari and dafalias 1997; Andrade and Borja 2007) that depends on the critical state parameters ((Γ, ϕ_{cs}, λ_{cs}), used to predict granular sand behaviors, obtained from by experimental testing, and specimen size can greatly affect the accuracy and reliability of these models.

It is commonly perceived that a large specimen provides a better representation of field soil behavior. However, the associated cost of materials used in the experimental testing limits the specimen size. Accordingly, several studies have proposed a minimum sizes for the direct shear and triaxial specimens to reduces or avoid specimen size effect. For example, the ASTM D3080 (2011) standard method for direct shear testing of soil requires a minimum specimen thickness of six times the maximum soil particle (D_{max}) diameter and minimum specimen width of 10xD_{max}. Similarly, ASTM D4767 and ASTMD7181 (2011) standard method for triaxial undrained and drained compression test requires cylindrical specimen with minimum diameter of the largest of 6xD_{max} or 33mm.

It is widely recognized that simple shear tests simulate field stress conditions expected during earthquakes more accurately than triaxial tests. The conclusions achieved by Yoshimi and Oh-oka (1975), through the performance of ring shear tests, were substantially opposite to those based on the

[1] Ph.D Student, Department of Civil Engineering, University of Tokyo
[2] Associate Professor, Institute of Industrial Science, University of Tokyo
[3] Lecturer, Department of Civil and Natural Resources Engineering, University of Canterbury, Christchurch, New Zealand

triaxial tests by Seed (1968). However, most of the above studies, shear strain was limited to 10%. Therefore, it is important to clearly understand the implications of changing the specimen size on extremely large shear strain.

Based on the above-mentioned background, the aim of this study is to better understand the role of specimen size on undrained cyclic resistance on the large deformation behavior of medium dense saturated sand during undrained cyclic loading.

TEST APPARATUS

The fully-automated torsional apparatus, shown in Figure 1, was used in this study for laboratory testing. This device was developed by Kiyota et al. (2008) in the Institute of Industrial Science, University of Tokyo, and is capable of achieving γ_{DA} levels exceeding 100% by using a belt-driven torsional loading system that is connected to an AC servomotor through electro-magnetic clutches and a series of reduction gears. Torque and axial load are measured by a two-component load cell, which is installed inside the pressure cell, having axial load and torque capacities of 8kN and 0.15kNm, respectively.
Difference in pressure levels between the cell pressure and the pore water pressure are measured by a high-capacity differential pressure transducer (HCDPT) with a capacity of over 600kPa. Volume change during the consolidation and initial shearing processes is measured by a low-capacity differential pressure transducer (LCDPT). An external potentiometer with a wire and a pulley is employed to measure large torsional deformations. Specified shear stress amplitude is controlled by a data acquisition system connected to a computer, which monitors the outputs from the load cell and calculates the shear stress. The measured shear stress is then corrected for the effects of the membrane force (Koseki et al. 2005), as described henceforward.

Toyoura sand (Gs = 2.659, e_{max} = 0.951, e_{min} = 0.608), which is a uniform sand with negligible fines content (Fc <0.1%), was used in this investigation. Its particle size distribution is shown in Figure 2. Four medium-size hollow cylindrical specimens with dimensions of 100mm in outer diameter, 60mm in inner diameter and 200mm in height were prepared by air pluviation method, thus producing a sand fabric with horizontal bedding planes (Sze and Yang 2014), at a relative density of 50±3% (Table 1).

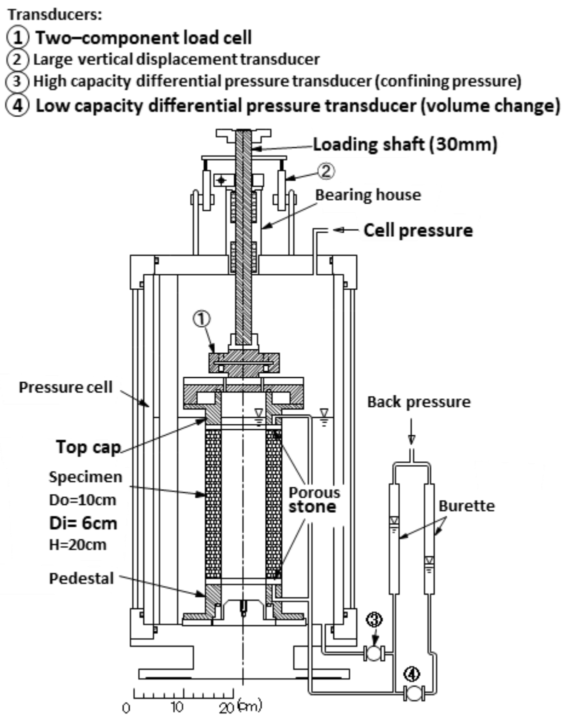

Figure1. Torsional shear apparatus employed in this study

Table: 1 List of Test Performed

Test	Relative Density Dr(%)	Shear stresses (kPa)	Mean effective stress (kPa)	Specimen size
		τ_{cyclic}	p_0’	
1	48.4	0.20	100	A
2	48.9	0.17	100	A
3	48.3	0.12	100	A
4	47	0.20	100	B
5	40.1	0.15	100	B
6	47	0.12	100	B
Specimen size A = Height 200, outer dia = 100mm, inner dia=60mm Specimen size B = Height 300, outer dia = 150mm, inner dia=90mm				

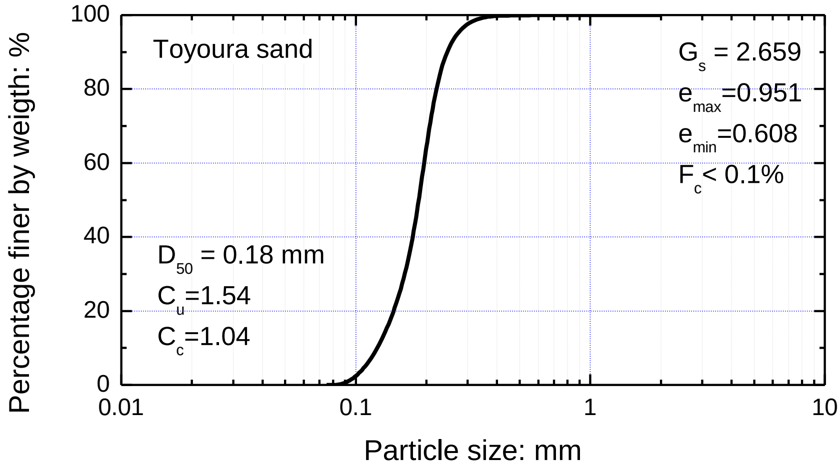

Figure 2. Particle size distribution of Toyoura sand

TEST PROCEDURE

Air pluviation technique was employed to make it possible to minimize the degree of inherent anisotropy in the radial direction (i.e. moving radially the nozzle of the pluviator and at the same time circumferentially in alternative directions, i.e. first in clockwise and then anti- clockwise directions, De Silva et al. 2006) of the hollow cylindrical sand specimens. Specimen preparation was carried out carefully by pouring the air-dried sand particles into a mold while the falling height was kept constant throughout the pluviation process to obtain specimens with uniform density

High degree of saturation (i.e. Skempton’s B-value > 0.95) was achieved by the double vacuum method (Ampadu, 1991), while circulating de-aired water into the specimens. The specimens were isotropically consolidated by increasing the effective stress state up to a p_0’ = 100 kPa, with a back pressure of 200 kPa. Subsequently, to replicate seismic conditions, a constant-amplitude undrained cyclic torsional shear stress (τ_{cyclic}) was applied at a shear strain rate of 0.5%/min. The loading direction was reversed when the amplitude of shear stress, which was corrected for the effect of membrane force, reached τ_{max} and τ_{min} target values. During the process of undrained cyclic torsional loading the vertical displacement of the top cap was prevented to mimic as much as possible the simple shear condition that ground undergoes during horizontal excitation.

RESULTS AND DISCUSSION

Effect on Membrane force

Koseki et al. (2005), among others, pointed out that in performing torsional shear tests on hollow cylindrical soil specimens, due to the presence of inner and outer membranes, the effect of membrane force on measured torsional shear stress cannot be neglected (i.e. to calculate the actual shear stress applied on soils, the total stress measured by the load cell needs to be corrected for the apparent shear stress induced by the presence of the membrane, namely membrane force). Furthermore, membrane force becomes significantly important when shear strain reaches an extremely large level (Kiyota et al. 2008; Chiaro et al., 2012).

Usually, the membrane force is corrected based on the linear elasticity theory, which assumes cylindrical deformation of a specimen. Accordingly, the theoretical apparent shear stress (τ_m) induced by the inner and the outer membranes can be evaluated as follows:

$$\tau_m = \frac{t_m E_m \left(r_o^3 + r_i^3\right)\theta}{\left(r_o^3 - r_i^3\right)H} \tag{1}$$

$$\theta = \frac{3\left(r_o^2 - r_i^2\right)H}{2\left(r_o^3 - r_i^3\right)}\gamma \tag{2}$$

here θ is the rotational angle of the top cap detected by external potentiometer; H is the height of the specimen; ro and ri are the outer and inner radii of the specimen; τ_m and Em are, respectively, the thickness and the Young's modulus (= 1470 kPa; Tatsuoka et al., 1986) of the membrane.

Nevertheless, experimental evidence clearly demonstrates that at large shear strains, deformation of a hollow cylindrical sand specimen is not uniform along specimen height. In addition, specimen shape is far from being perfectly cylindrical (Kiyota et al., 2010; Chiaro et al., 2013). Accordingly, to confirm the validity of Eq. (1) in correcting for the effect of the membrane force, an appropriate testing procedure was developed over the years (Kiyota et al., 2008; Chiaro et al., 2012; Chiaro et al., 2015a). Umar et. al (2016) showed the hyperbolic correlation between γ and τ_m for specimen size having height 300mm, outer diameter 150mm and inner diameter of 90mm. In order to validate the correlating, specimen dimensions was changed to height 200mm, outer diameter 100mm and inner diameter of 60mm.

A hollow cylindrical water specimen, monotonic torsional shear test was performed and results is plotted in Figure 3, to compare the specimen size effect on membrane force. From the Figure 3, it can be observed, changing the size of the membrane, membrane force is not greatly influenced. Therefore, it implies that existing correlation for the correction of membrane force is applicable irrespective of specimen dimensions.

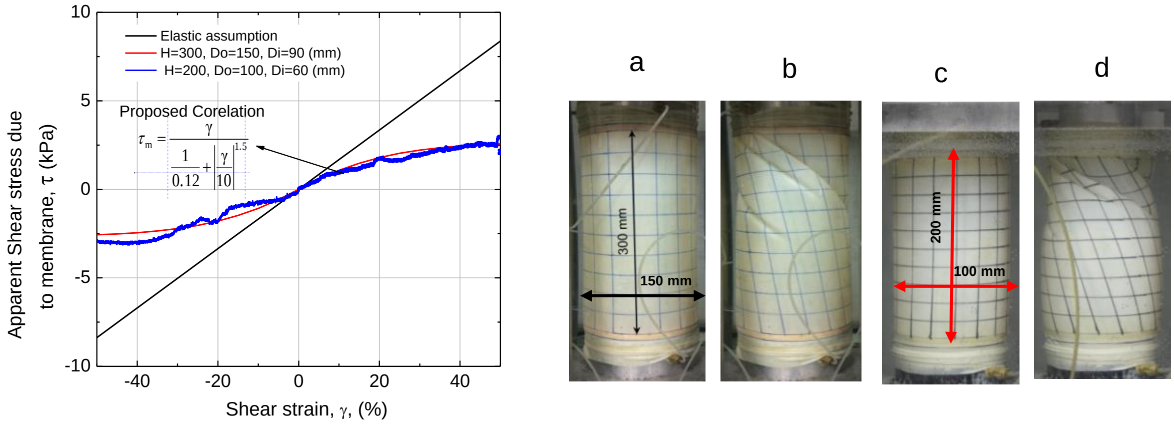

Figure 3: a) Comparison of membrane force between two different specimens

Undrained cyclic loading

The effect of specimen size on sand behavior during undrained shear is presented in the following paragraph with respect to excess pore water pressure generation and undrained cyclic shear strength. Typical test results describing the cyclic loading behavior of two Toyoura sand specimens subjected to cyclic stress ratio of 0.15 and 0.17 respectively are shown in Figure 4 and 5.

Figure 4 and 5 compares the undrained shear stress versus mean effective stress principal stress and shear strain of two different specimen size (Test No.2 and Test No.5) respectively. In Figure 4a, specimen type A, full liquefaction (i.e. the state of zero effective mean stress, p'= 0) was achieved in 10 loading cycles. Similarly, in Figure 4b, specimen type B, the state of $p' = 0$ was reached in 21 number of cycles. Cyclic mobility was observed in the effective stress path in different specimen size, where the effective stress recovered repeatedly after reaching the state of zero effective stress (i.e., full liquefaction). It was accompanied by a significant development of shear strain, as evidenced by the stress–strain relationship (Figure 5). The difference in the rate of excess pore water pressure generation could be related to the slight different in the relative density and stress ratio, which can also be evident from different stress-strain relationship in Figure 5.

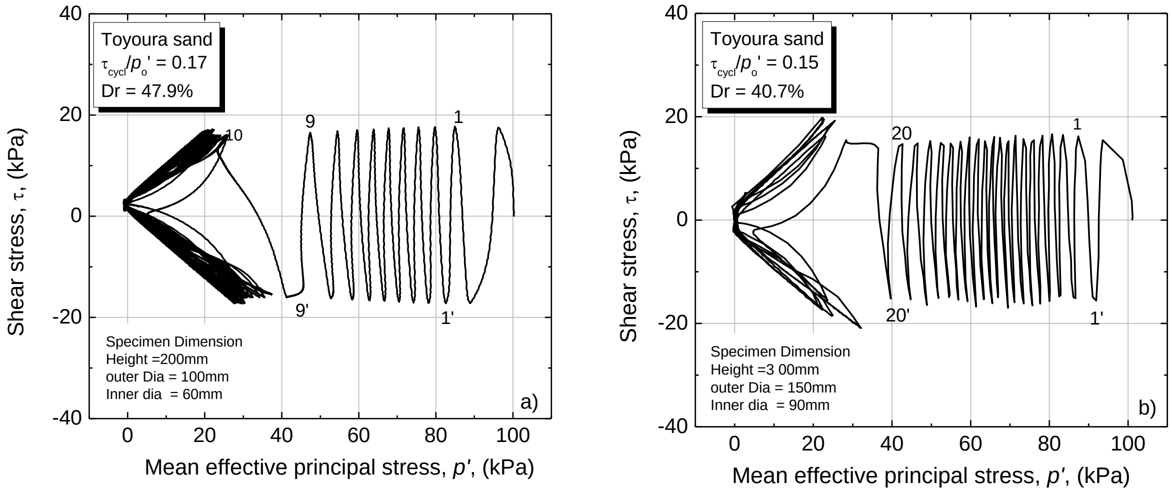

Figure 4: Typical test results of effective stress path a) Test No.2 b) Test no 5

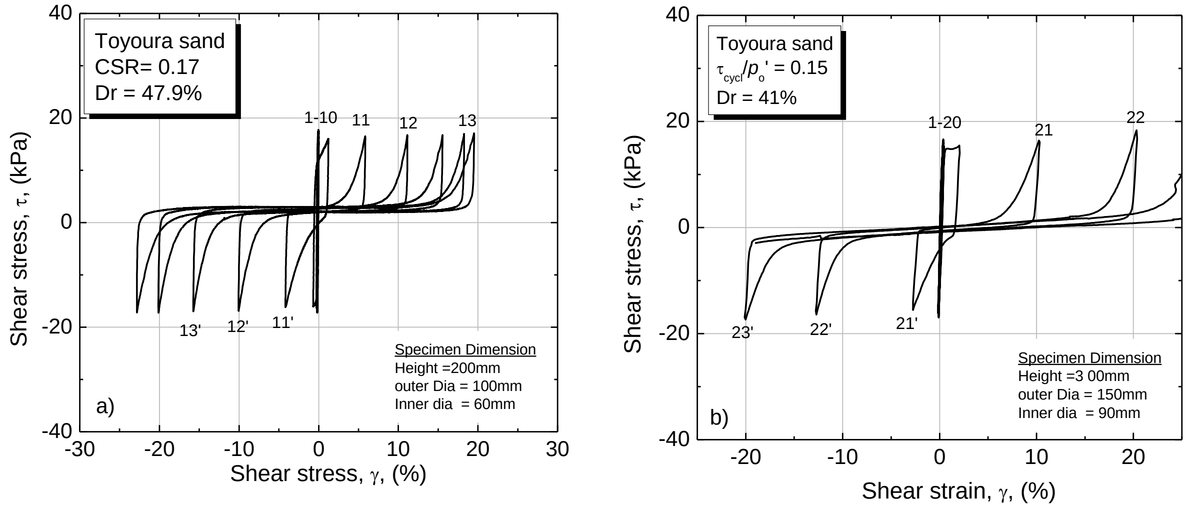

Figure 5: Typical test results of stress-strain relationship of Toyoura sand a) Test No.3 b) Test no 7

Resistance against liquefaction

Conventionally, the resistance to liquefaction or to cyclic strain accumulation of soils is evaluated as the number of cycles to develop a specific amount of double amplitude shear strain (γ_{DA}) during cyclic loading. Accordingly, Figure 6 compares the liquefaction resistance of different specimen sizes of Toyoura sand corresponding to a double amplitude shear strain (γ_{DA}) of 7.5%, which is equivalent a double amplitude shear strain of 5% in triaxial tests. It is evident, in spite of having different specimen size, Toyoura sand exhibits nearly same liquefaction resistance.

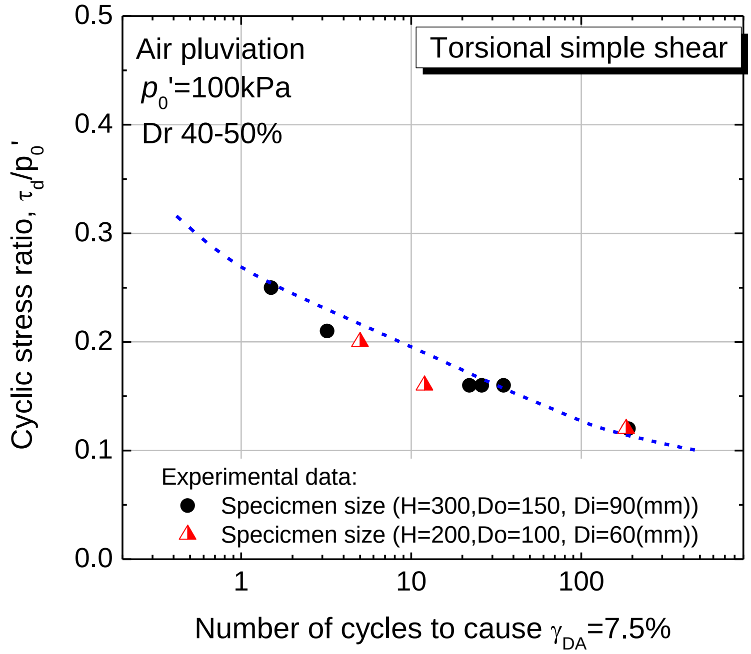

Figure 6: Liquefaction resistance comparison with specimen size

Effect of specimen size on strain localization

Failure of granular material is often characterize by the localization of non-uniform deformation commonly referred as shear band. Kiyota et al. (2008) found that the change in deviator stress q (= σ_v'- σ_h') response observed in undrained torsional shear tests, in which any vertical displacement of the top cap was prevented (i.e. to attain simple shear condition), to be consistent with the behavior observed during drained monotonic torsional shear tests by Tatsuoka et al. (1986). Kiyota et al.(2008) considered the state at which q is suddenly reduced, as the state at which formation of shear band takes place. Chiaro et al.2013) further confirmed that this state (sudden reduction of q) marks the initiation of formation of shear band and it is followed by a residual stress state after full development of shear band(s). In the previous studies conducted by Chiaro et al. (2015) and Umar et al. (2016), it was confirmed that strain localization is intrinsic property of granular material depending on relative density only, irrespective of the stress state. However, effect of specimen size can also be associated with strain localization and boundary conditions.

For Test No. 2 and 5, shear stress (τ) and deviator stress (q) variation with shear strain during undrained cyclic simple torsional shear loading (where the vertical displacement is prevented) is shown in Figure 8a and 8b, respectively. Note that in Fig. 7a and 7b, sudden drop of q can be observed at the shear strain of 27%, which is regarded as the initiation of the shear band within the specimen. This implies that, strain localization is purely dependent on the relative density of sand.

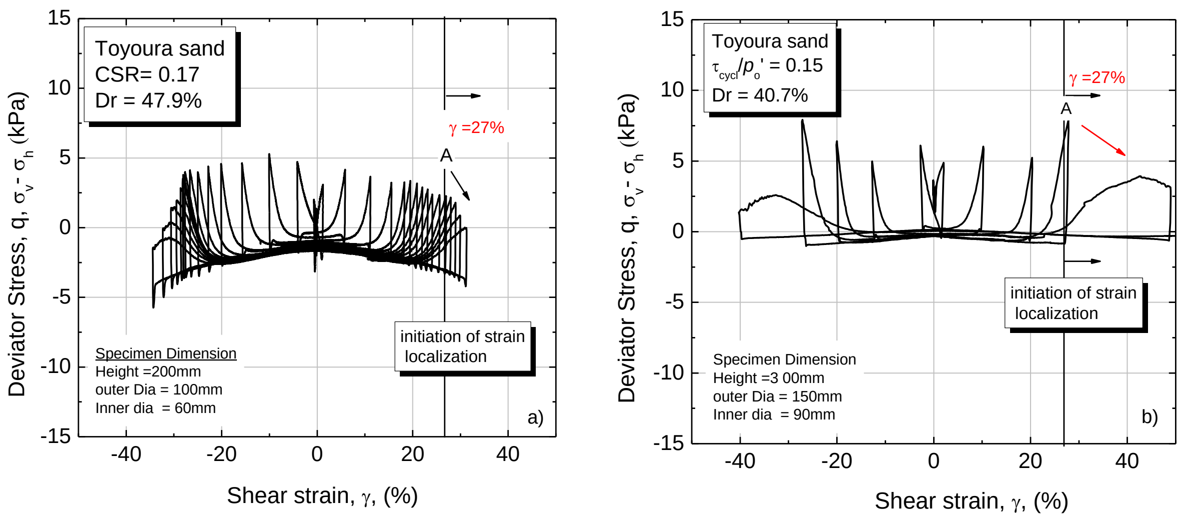

Figure 7: a) Comparison of undrained monotonic simple shear test

CONCLUSIONS

Undrained cyclic torsional shear loading tests with the modified torsional apparatus that is capable of achieving double amplitude shear strain up to about 100% were performed to investigate the effect of specimen size. Two series of test was performed on Medium dense (Dr 40-50%) Toyoura sand subjected to undrained cyclic loading. A parabolic relation is present for membrane correction force taking into account specimen size affect. Comparison of liquefaction resistance, which is evaluated at double amplitude shear strain (γ_{DA}) of 7.5%, is provided. The limiting value of the shear strain, at which initiation of strain localization appear during undrained shear loading test is evaluated by comparing the deviator stress (q) with shear strain(γ). It can be concluded from the above findings, specimen size of height=300mm, outer dia=150mm, inner dia=90mm and height=200mm, outer dia=100mm, inner dia=60mm, does not greatly influence the sand deformation behavior.

REFERENCES

Ampadu, S. I. K. (1991): Undrained behaviour of kaolin in torsional simple shear, Ph.D. Thesis, Dept. of Civil Engineering, University of Tokyo, Japan.

Andrade, J.E., and Borja, R.I. 2007. Modeling deformation banding in dense and loose fluid-saturated sands. Finite Elem. Anal. Design, 43: 361–383. doi:10.1016/j.finel.2006.11.012.

ASTM Standard D4767. 2011. Standard test method for consolidated undrained triaxial compression test for soils. ASTM International, West Conshohocken, Pa. www.astm.org. doi:10.1520/D4767-02

ASTM Standard D3080. 2011. Direct shear test of soils under consolidated drained conditions. ASTM International, West Conshohocken, Pa. www.astm.org. doi:10.1520/D3080_D3080M-11.

ASTM Standard D7181. 2011. Standard test method for consolidated drained triaxial compression test for soils. ASTM International, West Conshohocken,Pa. www.astm.org. doi:10.1520/D7181-11.

Chew, S.H., and Bharati, S.K. 2011. Effect of large diameter sample testing for offshore site investigation. In The 14th Pan-American Conference on Soil Mechanics and Geotechnical Engineering, Geo-Innovation Addressing Global Challenges, October 2–6, 2011, Toronto, Ont., Canada, pp. 1–6.

Chiaro, G., Koseki, J Sato, T. (2012) “Effects of initial static shear on liquefaction and large deformation properties of loose saturated Toyoura sand in undrained cyclic torsional shear tests.” Soil and foundations 2012; 52(3):498–510.

Chiaro, G., Kiyota, T. & Koseki, J. 2013. Strain localization characteristics of loose Toyoura sand in undrained cyclic torsional shear tests with initial static shear, Soils and Foundations, 53(1): 23-34.

Chiaro G., Koseki J. and Kiyota T. 2015. New insights into the failure mechanisms of liquefiable sandy sloped ground during earthquakes. Proceedings of the 6th International Conference on Earthquake Geotechnical Engineering, Christchurch, New Zealand, CD-ROM, 1-8.

De Silva, L. I. N., Koseki, J. and Sato, T. (2006): Effects of different pluviation techniques on deformation property of hollow cylinder sand specimens, Proc. of the International Symposium on Geomechanics and Geotechnics of Particulate Media, Ube, Yamaguchi, Japan, 29-33.

Ishihara, K., and Takatsu, H., (1977) "Pore Pressure Buildup in Initially Sheared Sand Subjected to Irregular Excitation," Proceedings of the 6th World Conference on Earthquake Engineering, New Delhi, India, 1977, pp. 2163-2168

Jefferies, M.G. 1993. Nor-Sand: a simple critical state model for sand. Geotechnique, 43(1): 91–103. doi:10.1680/geot.1993.43.1.91.

Kiyota, T., Sato, T., Koseki, J., and Mohammad, A. (2008): Behavior of liquefied sands under extremely large strain levels in cyclic torsional shear tests, Soils and Foundations, 48 (5), 727-739

Koseki, J., Yoshida, T. & Sato, T. 2005. Liquefaction properties of Toyoura sand in cyclic torsional shear tests under low confining stress, Soils and Foundations, 45(5): 103-113

Lee, K. L., and Seed, H. B., "Dynamic Strength of Anisotropically Consolidated Sand," Journal of the Soil Mechanics and Foundations Division, ASCE, Vol. 93, No. SM5, 1967, pp. 169-190.

Manzari, M.T., and Dafalias, Y.F. 1997. A critical state two-surface plasticity model for sands. Geotechnique, 47(2): 255–272. doi:10.1680/geot.1997.47.2.255.

Marsal, R.J. 1967. Large-scale testing of rockfill materials. Journal of Soil Mechanics and Foundations Division, ASCE, 93(SM2): 27–44.

Marachi, N.D., Chan, C.K., Seed, H.B., and Duncan, J.M. 1969. Strength and deformation characteristics of rockfill materials. Report No. TE-69(5), Department of Civil Engineering, University Of California, Berkeley, Berkeley, California.

Omar, T and Sadrekarimi, A, (2014): Specimen size effects on behavior of loose sand in triaxial compression tests, Canadian Geotechnical Journal, 52: 732-746 (2015)

Seed, H.B., 1968. Land slides during earthquakes due to soil liquefaction. Journal of the Soil Mechanics and Foundations Division, ASCE 94 (SM5), 1055–1122.

Sze, H. and Yang, J. (2014): Failure modes of sand in undrained cyclic loading: impact of sample preparation. Journal of Geotechnical and Geoenvironmental Engineering, ASCE, 140(1), 152-169.

Tatsuoka, F., Muramatsu, M. and Sasaki, T. (1982): "Cyclic undrained stress-strain behavior of dense sand by torsional simple shear test", Soils and Foundations, 22 (2), 55-69

Tatsuoka, F., Sonoda, S., Hara, K., Fukushima S. & Pradhan, T. B. S. (1986): "Failure and deformation of sand in torsional shear", Soils and Foundations, 26(4): 79-97.

Umar, M., Chiaro, G., Kiyota, T. 2016. On the influence of initial static shear on large deformation behavior of very loose Toyoura sand in undrained cyclic torsional shear tests, JGS Special Publication, 4: 17-22.

Yang, J. and Sze, H. (2011). "Cyclic Strength of Sand under Sustained Shear Stress." *J. Geotech. Geoenviron. Eng.*, 10.1061/(ASCE)GT.1943-5606.0000541, 1275-1285.

Yoshimi, Y. and Oh-oka, H. (1975): "Influence of degree of shear stress reversal on the liquefaction potential of saturated sand", Soils and Foundations, 15 (3), 27-40