On the influence of initial static shear on large deformation behavior of very loose Toyoura sand in undrained cyclic torsional shear tests

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ABSTRACT

This paper reports on the influence of initial static shear on large deformation behavior of very loose ($D_r = 24$-30%) Toyoura sand subjected to undrained cyclic torsional loading. A series of isotropically consolidated torsional simple shear tests were carried out on hollow cylindrical specimens up to single amplitude shear strain exceeding 50%. Two types of cyclic loading patterns, namely reversal stress and non-reversal stress, were employed by varying the magnitude of combined initial static shear and cyclic shear stresses. The observed types of failure were distinguished as liquefaction and residual deformation based on the difference in the effective stress paths and the modes of development of cyclic residual shear strain. Test results revealed that, similar to the case of medium-dense Toyoura sand ($D_r = 44$-50%) previously investigated by the Authors, under reversal stress loading, failure could be associated with liquefaction followed by extremely large deformation during cyclic mobility. Contrarily, under non-reversal stress loading, a progressive accumulation of residual deformation brought specimens to failure although liquefaction did not occur. Moreover, the presence of initial static shear does not always lead to a decrease in the liquefaction resistance or strain accumulation of very loose sand. In fact, its resistance can increase or decrease with an increase in initial static shear stress, but it strongly depends on the combination of static and cyclic shear stresses and, thus, on the type of loading. However, under the same magnitude of combined shear stresses applied, very loose sand is much weaker against large cyclic shear strain accumulation than the medium-dense sand.

Key Words: liquefaction, large strain, initial static shear stress, residual deformation, torsional shear test

1 INTRODUCTION

Liquefaction of saturated loose sandy deposits is a major cause for large ground deformations and catastrophic failure of natural and manmade slopes, embankments, levees etc. during and after earthquakes. For example, disastrous slope failures due to liquefaction were observed during the 1964 Niigata Earthquake, Japan, and the 1964 Great Alaskan Earthquake, USA (Hamada et al., 1994). In 1971, the San Fernando earth-dam liquefied and collapsed during a powerful earthquake that hit Southern California, USA (Seed et al., 1975). More recently, during the 2011 Canterbury Earthquake Sequence (New Zealand) and the 2011 Off the Pacific Coast of Tohoku Earthquake (Japan), extensive liquefaction-induced lateral spreading occurred in sloped ground and produced severe damage to residential houses and buildings, industrial and commercial structures, road and bridge infrastructures, lifeline facilities and levees (Cubrinovski et al. 2010, 2011; Kiyota et al., 2011; among others). Lateral spreading and liquefaction were also observed in a gentle slope nearby a damaged earth dam-embankment following the 2015 Gorkha Nepal Earthquake (Goda et al., 2015; Chiaro et al., 2015b).

The role of initial static shear on the undrained cyclic behavior of sandy soils has been long investigated by means of well-controlled laboratory testing, namely conventional triaxial apparatus (Lee et al., 1967; Vaid et al., 1983, Hyodo et al., 1991; Yang and Sze, 2011; among others), or using simple shear devices, which can simulate field stress conditions expected during earthquakes more accurately than triaxial apparatus (Yoshimi et al., 1975; Vaid et al., 1979; Tatsuoka et al., 1982; Chiaro et al., 2012 and 2013). The major conclusion from these studies is that the initial static shear stress has a significant effect on the liquefaction resistance of sandy soils, in conjunction with the earthquake-induced cyclic shear stress, the soil relative density, confining pressure, among other factors.

Nevertheless, most of these previous studies have a tendency to focus on the liquefaction resistance or cyclic strength of sand in sloped ground, defined as the relationship between the cyclic stress ratio and the number of loading cycles to cause liquefaction or a
given double amplitude shear strain of 5% in triaxial tests or 7.5% in simple shear tests. Thus, investigations have been lacking into the fundamental aspect of cyclic behavior, such as how the presence of initial static shear influences the extremely large deformation response of sand, including the effective stress path, stress-strain relationship, excess pore water pressure generation and deformation pattern. Such knowledge is required since it can provide new and useful understandings into the failure mechanisms of liquefied sand and consequent development of extremely large deformation.

Moreover, as the Authors investigated in the literature, there exists no experimental data describing extremely large deformation behavior of very loose sand (D_r < 30%) subjected to undrained cyclic shear loading with initial static shear. This is due mainly to mechanical limitations of conventional testing apparatus and/or due to large extents of non-uniform deformation of very loose specimens at higher strain levels, as well as technical difficulties in correcting for the effects of membrane force during the tests. Consequently, the shear strain levels employed were limited to the range of 10% to 20%.

Accordingly, in this study, to gain a better understanding on the effects of initial static shear on large deformation behavior of very loose sand subjected to undrained cyclic loading, a series of torsional simple shear tests were carried out on hollow cylindrical specimens of Toyoura sand having a D_r = 24-30% and subjected to single amplitude shear strain exceeding 50%.

2 STRESS CONDITIONS IN SLOPED GROUND DURING EARTHQUAKES

As schematically shown in Fig. 1, before an earthquake, a soil element beneath sloped ground is subjected to an initial static shear stress (τ_{static}) induced by slope inclination conditions. During an earthquake, due to the superimposition of static shear stress (τ_{static}) with cyclic shear stress (τ_{cyclic}), the soil element experiences partially reversed or non-reversed shear stress loading conditions.

Specifically, when τ_{static} < τ_{cyclic}, the shear stress changes during each loading cycle within a maximum positive value (τ_{max} = τ_{static} + τ_{cyclic} > 0) to a minimum negative value (τ_{min} = τ_{static} - τ_{cyclic} < 0). This type of loading is known as reversal stress or two-way loading. On the other hand, when τ_{static} > τ_{cyclic}, the shear stress is always positive (i.e. τ_{max} > 0 and τ_{min} > 0). Consequently, non-reversal stress or one-way loading takes place (Yoshimi and Oh-oka, 1975; Hyodo et al., 1991; among others).

3 TEST APPARATUS

In this study, laboratory testing was carried out using the fully-automated torsional apparatus shown in Fig. 2, which was developed by Kiyota et al. (2008) in the Institute of Industrial Science, University of Tokyo.

Such a device is capable of achieving double amplitude shear strain levels exceeding 100% by using a belt-driven torsional loading system that is connected to an AC servo motor 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 8 kN and 0.15 kNm, respectively.
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 (Chiaro et al., 2015a).

4 TEST PROCEDURE

Toyooura sand ($G_s = 2.659, e_{\text{max}} = 0.951, e_{\text{min}} = 0.608$), which is a uniform sand with negligible fines content ($F_c < 0.1\%$), was used during this investigation. Six medium-size hollow cylindrical specimens with dimensions of 150 mm in outer diameter, 90 mm in inner diameter and 300 mm 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 $27 \pm 3\%$.

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

High degree of saturation (i.e. Skempton’s B-value > 0.96) 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 $p_{\text{oa}} = 100$ kPa, with a back pressure of 200 kPa. Subsequently, to replicate seismic conditions, a constant-amplitude undrained cyclic torsional shear stress ($\tau_{\text{cyclic}}$) was applied at a shear strain rate of $0.5\%/\text{min}$. The loading direction was reversed when the amplitude of shear stress, which was corrected for the effect of membrane force, reached $\tau_{\text{max}}$ and $\tau_{\text{min}}$ 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. Note that, in some tests drained monotonic shearing was applied before the undrained one in order to achieve a specified value of initial static shear ($\tau_{\text{static}}$), representing sloped ground condition.

To consider various combinations of initial static and cyclic shear stresses, tests were performed over a wide range of initial static shear varying from 0 to 25 kPa, while applying a cyclic shear stress of 16 kPa (see test detail in Table 2).

Table 2. Undrained cyclic torsional simple shear tests performed in this study.

| Test | $D_i$ (%) | Shear stresses ($\tau_{\text{max}}, \tau_{\text{cyclic}} + \tau_{\text{static}}$ (kPa)) | Type of Loading |
|------|-----------|---------------------------------|----------------|
| 1    | 24.1      | $\tau_{\text{cyclic}}$, $\tau_{\text{static}}$, $\tau_{\text{max}}$, $\tau_{\text{min}}$ | Reversal       |
| 2    | 25.7      | $\tau_{\text{cyclic}}$, $\tau_{\text{static}}$, $\tau_{\text{max}}$, $\tau_{\text{min}}$ | Reversal       |
| 3    | 25.6      | $\tau_{\text{cyclic}}$, $\tau_{\text{static}}$, $\tau_{\text{max}}$, $\tau_{\text{min}}$ | Reversal       |
| 4    | 29.8      | $\tau_{\text{cyclic}}$, $\tau_{\text{static}}$, $\tau_{\text{max}}$, $\tau_{\text{min}}$ | Reversal       |
| 5    | 28.1      | $\tau_{\text{cyclic}}$, $\tau_{\text{static}}$, $\tau_{\text{max}}$, $\tau_{\text{min}}$ | Non- Rev.      |
| 6    | 28.9      | $\tau_{\text{cyclic}}$, $\tau_{\text{static}}$, $\tau_{\text{max}}$, $\tau_{\text{min}}$ | Non- Rev.      |

Effective mean principal stress, $p_{\text{oa}}' = 100$ kPa

5 TEST RESULTS

5.1 Correction for 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 ($\tau_m$) induced by the inner and the outer membranes can be evaluated as follows:

$$\tau_m = \frac{r_m E_m r_3^3 + r_1^3 \theta}{r_3^3 - r_1^3} H$$

(1)

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

(2)

where $\theta$ is the rotational angle of the top cap detected by external potentiometer; $H$ is the height of the specimen; $r_o$ and $r_i$ are the outer and inner radii of the specimen; $l_m$ and $E_m$ are, respectively, the thickness (= 0.3 mm in this study) 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 apposite testing procedure was
developed over the years (Kiyota et al., 2008; Chiaro et al., 2012; Chiaro et al., 2015a).

Thus, in this study, the shear stress was corrected for the effect of membrane force by employing the empirical hyperbolic correlation between $\gamma$ and $\tau_{max}$ obtained by Chiaro et al. (2015a) by means of monotonic and cyclic torsional shear tests carried out on two hollow cylindrical water specimens (Fig. 3).

5.2 Undrained cyclic torsional shear behavior of very loose sand

Typical test results describing the cyclic loading behavior of two very loose Toyoura sand specimens subjected to different levels of static shear stress and stress loading conditions are shown in Figs. 4 and 5.

Figure 4 shows the results of reversal stress Test No. 2 ($\tau_{cyclic} = 16$ kPa; $\tau_{static} = 5$ kPa). In this test, full liquefaction (i.e. the state of zero effective mean stress, $p' = 0$) was achieved in 6 loading cycles. It is noted that, only small shear strain levels were developed within the first 5 loading cycles, while limited flow took place in the sixth cycle where $\gamma$ suddenly reached about 10%. This phase was followed by cyclic mobility as observed in Fig. 4(a), where the effective stress recovered repeatedly. It was accompanied by flow-type failure with a significant development of shear strain as evidenced by the stress-strain relationships (Fig. 4(b)).

Figure 5 shows the results of non-reversal stress Test No. 5 ($\tau_{cyclic} = 16$ kPa; $\tau_{static} = 20$ kPa). In this case, even though full liquefaction did not occur, a large shear strain level exceeding 50% could be reached. Moreover, in this test, a relatively high shear strain level of 20% was achieved during the first cycle. It was then followed by a more progressive development of shear strain up to $\gamma = 40\%$, after which a sudden development of shear strain took place due to formation of shear band(s) within the specimen, as displayed in Fig. 6.
5.3 Residual deformation development of sand with initial static shear

To better examine the effects of initial static shear on the large deformation properties of very loose Toyoura sand in undrained cyclic torsional shear tests, the observed modes of development of residual shear strain associate with reversal stress and non-reversal stress loadings are shown in Fig. 7. Note that residual shear strain (γR) refers to the single amplitude shear strain value measured at r = rmax.

In the case of reversal stress, the higher the rstatic the lower the number of cycles necessary to reach extremely large residual shear strain. In addition, it is noted that only following the achievement of full liquefaction state (p* = 0), large residual shear strain was developed in just a few loading cycles. These test results, clearly highlight the detrimental effect of rstatic in combination with γcyclic, which reduces the number of cycles to the onset of liquefaction and the catastrophic development of extremely large residual shear strain in the post-liquefaction stage. On the other hand, in the case of non-reversal stress, extremely large residual shear strain could be achieved progressively only by applying a large number of cycles.

![Development of residual shear strain](image)

**Fig. 7.** Development of residual shear strain.

5.4 Resistance to cyclic strain accumulation

With reference to level ground conditions, cyclic liquefaction resistance is expressed as the cyclic stress ratio (CSR = τcyclic/p0') required to develop a specific amount of double amplitude shear strain (γDA) during cyclic loading. However, in the case of sloped ground, due to the presence of initial static shear, SSR (τstatic/p0') is a more suitable parameter to describe the effects of initial static shear on the resistance to liquefaction or cyclic strain accumulation. Moreover, shear strain development is usually more predominant in the direction where the static shear is applied. Therefore, γDA becomes unsymmetrical. Consequently, in order to have better understanding of liquefaction resistance to cyclic strain accumulation in the case of initial static shear, Chiaro et al. (2012) suggested the use of single amplitude shear strain (γSA) rather than γDA to evaluate liquefaction or cyclic shear resistance of sands.

Figure 8 compares the cyclic strain resistance of very loose Toyoura sand for different levels of γSA (reversal stress) or γR (non-reversal stress) i.e. 7.5%, 20% and 50%. Interestingly, it is noted that, in the case of 7.5% the sand resistance decreases with an increase in SSR. At larger strains, however, the sand resistance first decreases and then increases upon the non-reversal stress line. This is consistent with the behavior observed by Chiaro et al. (2012) for the case of medium-dense Toyoura sand (Dr = 44-50%) tested under the same testing conditions, as shown in Fig. 9.

Comparison between test results by Chiaro et al. (2012) and those obtained in this study indicates that, in general, despite the different level of relative density, Toyoura sand behavior is reasonably similar. In fact, under reversal stress loading, a drastic drop in the liquefaction resistance is observed as the initial static shear increases. However, under non-reversal stress, cyclic strain accumulating resistance increases with the initial static shear increase. As expected, it is clear that the very loose sand is much weaker against liquefaction/cyclic strain accumulation, so that full liquefaction state and extremely large deformation are achieved in less number of loading cycles under the same CSR.

![Large cyclic strain resistance of very loose Toyoura sand](image)

**Fig. 8.** Large cyclic strain resistance of very loose Toyoura sand.

![Comparison between cyclic strain resistance of very loose and medium-dense Toyoura sand](image)

**Fig. 9.** Comparison between cyclic strain resistance of very loose and medium-dense Toyoura sand.
6 CONCLUSIONS

The influence of initial static shear on large cyclic deformation behavior of very loose Toyoura sand ($D_r = 24-30\%$) was evaluated by conducting a series of undrained cyclic torsional simple shear tests. It was found that Toyoura sand behaves in two different ways depending on the combined shear stress ($\tau_{\text{static}} + \tau_{\text{cyclic}}$). In the case of reversal stress loading ($\tau_{\text{static}} < \tau_{\text{cyclic}}$), the sand easily liquefied and large deformation developed while showing cyclic mobility. On the other hand, in the case of non-reversal stress loading ($\tau_{\text{static}} > \tau_{\text{cyclic}}$), a progressive accumulation of residual deformation brought specimens to failure. This is consistent with previous test results obtained by the Authors for medium-dense Toyoura sand ($D_r = 44-50\%$). Likewise, the presence of initial static shear does not always lead to a decrease in the liquefaction resistance/cyclic strain accumulation of very loose sand. In fact, it can increase or decrease with an increase in initial static shear stress, but it strongly depends on the combination of static and cyclic shear stresses and thus on the type of loading. However, as anticipated, under the same magnitude of cyclic stress ratio (CSR) applied, very loose sand is much weaker against large cyclic strain accumulation than the medium-dense sand.

REFERENCES

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

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

3) Chiaro, G., Kiyota, T. and Miyamoto, H. (2015a): Large deformation properties of reconstituted Chrishchud sand subjected to undrained cyclic torsional simple shear loading, Proc. of the 2015 NZSEE Conference, Rotorua, New Zealand, April 2015, 529-536.

4) Chiaro, G., Kiyota, T., Pokhrel, R. M., Goda, K., Katagiri, T. and Sharma, K. (2015b): Reconnaissance report on geotechnical and structural damage caused by the 2015 Gorkha Earthquake, Nepal. Soils and Foundations, 55(5): 1030-1043.

5) Chiaro, G., Koseki, J. and Kiyota, T. (2015c): New insights into the failure mechanisms of liquefiable sandy sloped ground during earthquakes. Proc. of the 6th International Conference on Earthquake Geotechnical Engineering, Christchurch, New Zealand, Nov. 2015, CD-ROM, p.8.

6) Chiaro, G., Koseki, J. and 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, Soils and Foundations, 52(3), 498-510.

7) Cubrinovski, M., Bray, J. D., Taylor, M., Giorgini, S., Bradley, B. A., Wotherspoon, L. and Zupan, J. (2011): Soil liquefaction effects in the Central Business Districts during the February 2011 Christchurch Earthquake. Seismological Research Letters, 82(6), 893-904.

8) Cubrinovski, M., Green, R.A., Allen, J., Ashford, S. A., Bowman, E., Bradley, B. A., Cox, B., Hutchinson, T. C., Kavazanjian, E., Orense, R. P., Pender, M., Quigley, M. and Wotherspoon, L. (2010): Geotechnical reconnaissance of the 2010 Darfield (Canterbury) Earthquake, Bulletin of the NZSEE, 42(4): 243-320.

9) 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.

10) Goda, K., Kiyota, T., Pokhrel, R. M., Chiaro, G., Katagiri, T., Sharma, K. and Wilkinson, S. (2015): The 2015 Gorkha Nepal Earthquake: insights from earthquake damage survey, Frontiers in Built Environment, 1(8): 1-15.

11) Hamada, M., O’Rourke, T. D. and Yoshida, N. (1994): Liquefaction-induced large ground displacement, Performance of Ground and Soil Structures during Earthquakes, 13th ICMSFE, 93-108.

12) Hyodo, M., Murata, H., Yasufuku, N. and Fujii, T. (1991): Undrained cyclic shear stress and residual shear strain of saturated sand by cyclic triaxial tests, Soils and Foundations, 31(3), 60-76.

13) Kiyota, T., Koseki, J. and Sato, T. (2010): Comparison of liquefaction-induced ground deformation between results from undrained cyclic torsional shear tests and observations from previous model tests and case studies, Soils and Foundations, 50(3), 421-429.

14) Kiyota, T., Kyokawa, H. and Konagai, K. (2011): Geo-disaster report on the 2011 Tohoku-Pacific Coast Earthquake. Bulletin of Earthquake Resistant Structure Research Center, 44, 17-27.

15) 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.

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

17) Lee, K. L., and Seed, H. B. (1967): Dynamic strength of anisotropically consolidated sand, Journal of Soil Mechanics and Foundations Division, ASCE, 93(SM5): 169-190.

18) Seed, H. B., Idriss, I. M., Lee, K. L. and Makadisi, F.I. (1975): Dynamic analysis of the slide in the Lower San Fernando Dam during the Earthquake of February 9, 1971, Journal of Geotechnical Engineering Division, ASCE, GT9, 889-911.

19) 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.

20) 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.

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

22) Vaid, Y. P. and Chern, T. C. (1983): Effect of static shear on resistance to liquefaction, Soils and Foundations, 23(1), 47-60.

23) Vaid, Y. P. and Finn, W.D.L. (1979): Static shear and liquefaction potential, Journal of Geotechnical Engineering Division, ASCE, 105(GT10), 1233-1246.

24) Yang, J. and Sze, Y. (2011): Cyclic behavior and resistance of saturated sand under non-symmetrical loading conditions. Geotechnique, 61(1), 59-73.

25) 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.