EFFECT OF UNDRAINED CYCLIC STRAIN HISTORY ON STRENGTH CHARACTERISTICS OF CLEAN SAND IN TORSIONAL SHEAR TESTS

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ABSTRACT:

In this study the effect of cyclic loading on the post-liquefaction shear strength of clean sands (Silica and Toyoura sand) has been investigated using modified torsional shear apparatus. Multistage loading tests were performed on hollow cylindrical specimen, constant amplitude cyclic shear stress was applied to induce cyclic shear strain (damage strain γ_{Δ}) up to required level, then monotonic loading was applied in undrained condition. The test results showed that the γ_{Δ} has significant influence on the peak undrained shear strength of both sands. Moreover, the test results revealed that by inducing 26 % of γ_{Δ} peak undrained shear strength of sands degraded up to 60% of the original strength without γ_{Δ}.

Key Words: *Post-liquefaction, Undrained Strength, Torsional Shear, Large Strain*

INTRODUCTION

After 1964 Niigata earthquake Japan, liquefaction was recognized as one of the most devastating phenomena in which soil loses its shear strength and undergo extremely large deformation. Damages caused by the liquefaction includes landslides, substantial settlement, damages to the infrastructure and earth-fill structures. For instance, in 1971 San Fernando earth-fill dam liquefied and collapsed during Sylmar earthquake that hit Southern California, USA (Rouholamin et al.[1)]). After the investigation by Seed et al.,[2)] it was concluded that the dam was constructed by sandy material, the fill material was in loose state, and the earthquake shaking resulted the liquefaction. While recently during 2011 Off the Pacific coast of the Tohoku Earthquake, approximately 15% of the irrigation earth-fill dams were significantly damaged (Japan Rural Development Bureau) [3)]. The most serious case was the collapse of the Fujinuma dam that resulted in the over-topping leading to flooding (Tanaka et al. [4)])and Duttine et al.[5)]). A possible scenario of the Fujinuma dam failure investigated by Tatsuoka et al.[6)] was the degradation of undrained strength of the dam body formed by sandy soil during the earthquake.

The evaluation of post-liquefaction undrained shear strength plays an important role in the estimation of post-liquefaction deformation, as stress-strain properties of soils are required to estimate the post-liquefaction deformation. Several experimental and theoretical research works have been carried out to assess the liquefaction-induced deformation. Seed et al.[7)] investigated the post-liquefaction behavior of dams and they concluded that after liquefaction soil regain its strength and stiffness on further shearing. Later on, Vaid et al.[8)] investigated post-liquefaction behavior of Fraser River sand, by undrained cyclic loading followed by monotonic loading. They concluded that sand showed zero stiffness up-to threshold

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strain level during monotonic loading. The sand behavior transited to strain hardening after threshold strain with the increase in the stiffness and strength. Yasuda et al.[9] observed similar strain hardening behavior with Toyoura sand and referred as “reference strain”. While Shamoto et al. [10] also observed the post-liquefaction strain hardening behavior in torsional shear tests. They noticed that post-liquefaction shear stress-shear strain curves were parallel, but stiffness increased at different shear strain levels.

Previous studies have been focused on the post-liquefaction deformation, while in this study post-liquefaction undrained strength characteristics of clean sands (fine content < 1%) up to large strain level was investigated using modified torsional shear apparatus (Kiyota et al.[11]). To investigate the influence of cyclic shear strain (damage strain γ_Δ) on post-liquefaction strength characteristics, multistage undrained tests (i-e cyclic loading followed by monotonic loading) were performed. The post-liquefaction behavior with various γ_Δ was compared with that without γ_Δ in terms of undrained peak strength and excess pore water pressure generation.

MATERIAL, TEST APPARATUS, AND PROCEDURE

Two types of clean sand with comparable grain size distribution were used in this study, Silica sand No.7 and Toyoura sand. Grain shape and texture can be seen in the microscopic pictures of both sands shown in Figure 1, while index properties are enlisted in table 1. The grain size distribution of both sands is demonstrated in Figure 2. While Table 2 provides the list of tests performed in this study.

Torsional shear apparatus modified by Kiyota et al.[11] was used for the experiments, shown in Figure 3. It can achieve double amplitude shear strain level of 120%. It was operated by using a belt-driven torsional loading system connected to an AC servo motor through electromagnetic clutches and a series of reduction gears. A high-capacity differential pressure transducer with a capacity of over 600 kPa was used to measure the pressure difference between the cell pressure and the pore water pressure. While low-capacity pressure transducer was used to measure volume change during consolidation by the difference in water level between two burettes. Two-component loadcell was used to measure torque moment and axial load with measuring capacity up to 0.15 kNm and 8 kN, respectively. Torsional deformation was calculated from the degree of the rotation of the specimen top cap which was measured by an external potentiometer with a wire and a pulley. The shear stress amplitude was controlled through a computer that controls and monitors the output from the load cell. The measured shear stress was corrected for the membrane force (Chiaro et al. [12].).

Dry air pluviation method was used to prepare hollow specimens of 200 mm height, 100 mm outer diameter and 60 mm inner diameter. Air-dried sand was poured through a funnel keeping at a constant height to achieve uniform relative density of 47 ± 3 %. Subsequently, specimens were kept under a vacuum for about 90 minutes to remove the air entrapped inside the voids (Ampadu et al. [13]). Afterwards specimens were saturated, by circulating de-aired water to achieve B value (Skempton's coefficient of saturation) greater than 0.95. After saturation specimens were isotropically consolidated to mean effective principal stress of 100 kPa at a constant backpressure of 200 kPa (Figure 4, State A to B).

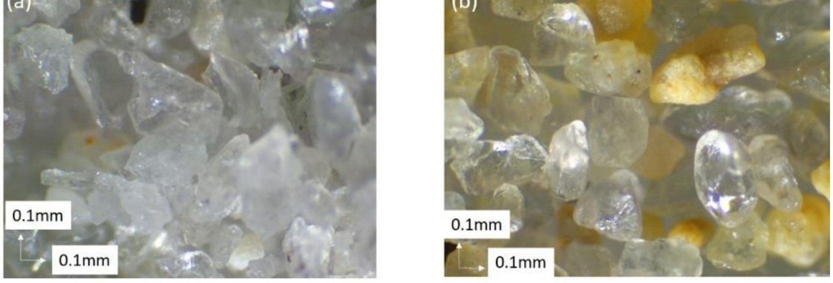

Figure 1. Microscopic picture with 4x optical zoom (a) Silica #7 (b) Toyoura sand

Table 1. Material Properties

Material	Specific gravity, Gs	Min void ratio, e_{min}	Max void ratio e_{max}	Mean diameter, D_{50} (mm),	Fines content, FC %
Silica #7	2.617	0.639	1.145	0.21	0.1
Toyoura Sand	2.659	0.610	0.951	0.18	0.1

Table 2. List of Tests Performed

Test	Material used	Relative density, *Dr* (%)	Cyclic stress ratio, $CSR = \tau_{cyclic}/p_0'$	Damage strain, γ_Δ (%)	Type of loading
TEST No. 1	Silica #7	50.3	-	0	Monotonic
TEST No. 2	Silica #7	47.6	± 0.2	8	Multistage
TEST No. 3	Silica #7	46.0	± 0.2	18	Multistage
TEST No. 4	Silica #7	48.3	± 0.2	26	Multistage
TEST No. 5	Toyoura sand	47.4	-	0	Monotonic
TEST No. 6	Toyoura sand	51.0	± 0.2	7	Multistage
TEST No. 7	Toyoura sand	45.8	± 0.2	15	Multistage
TEST No. 8	Toyoura sand	44.2	± 0.2	26	Multistage

The specimens were subjected to a two-stage loading hereby will be referred to as multistage loading Yasuda et al.[14)]. In multistage loading procedure, in the first stage specimens were subjected to constant amplitude cyclic stress ratio ($CSR = \tau_{cyclic}/p_0'$) of 0.20 until desired damage strain (γ_Δ) amplitude was reached (Figure 4, State B to C). The γ_Δ is defined as the difference between maximum shear strain (γ_{max}) and minimum shear strain (γ_{min}) developed during cyclic loading as illustrated in Figure 5. In the second stage, while keeping the undrained condition, specimens were loaded monotonically until the single amplitude of shear strain of 50%. All the tests were performed under a constant strain rate of 0.5%/min.

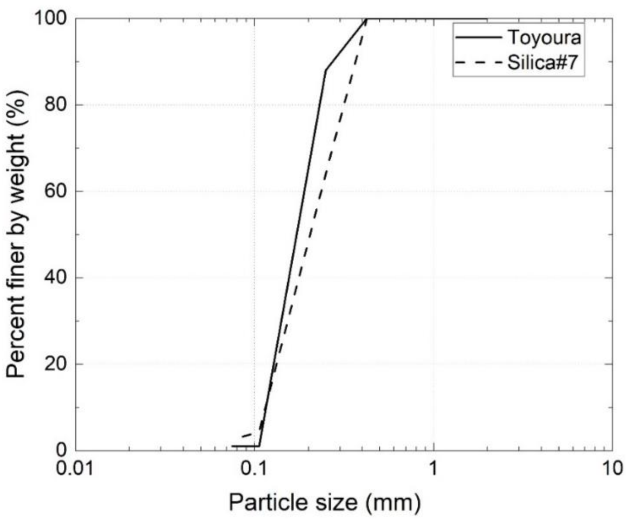

Figure 2. Particle size distribution of Silica sand No. 7 and Toyoura sand used in this study.

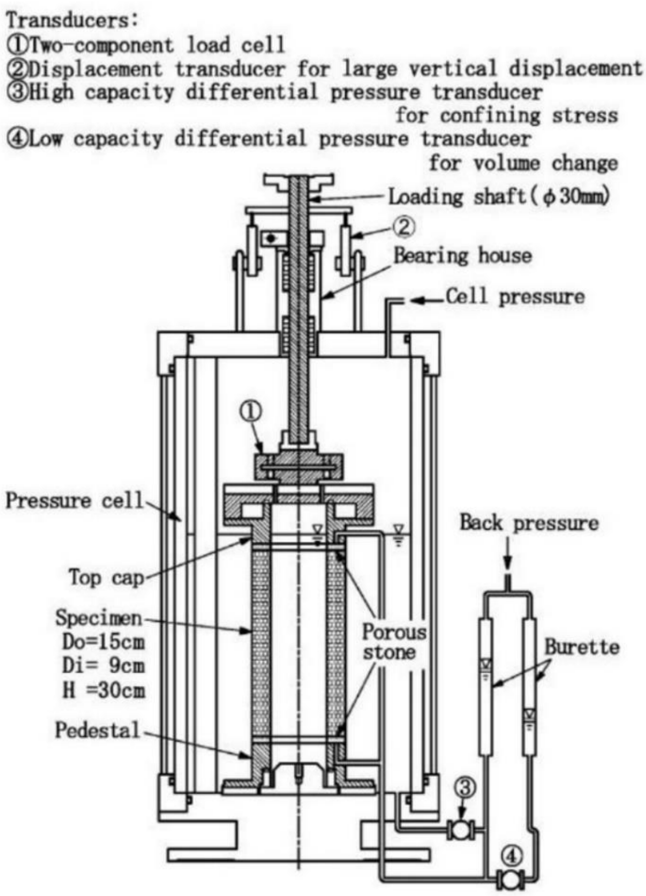

Figure 3. Torsional shear apparatus used in this study (Kiyota et al.[10])

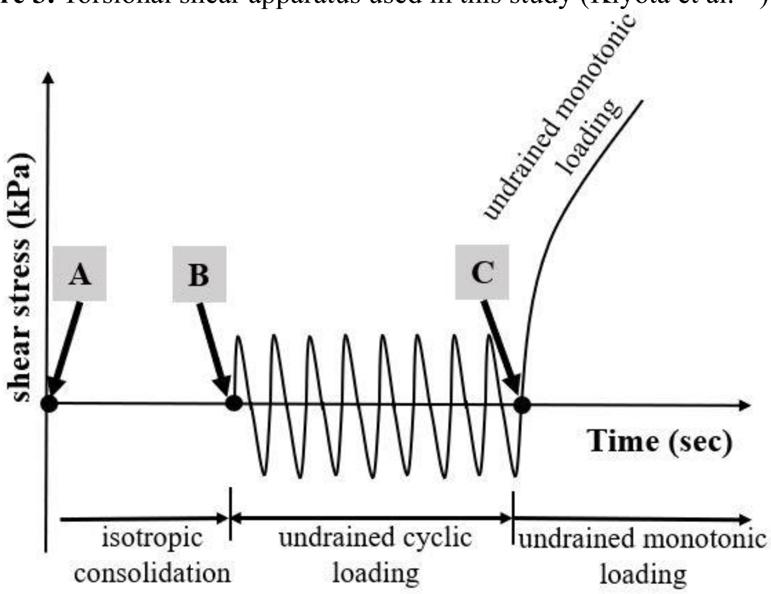

Figure 4. Test procedure to investigate post-liquefaction shear strength after Yasuda et al.[14]

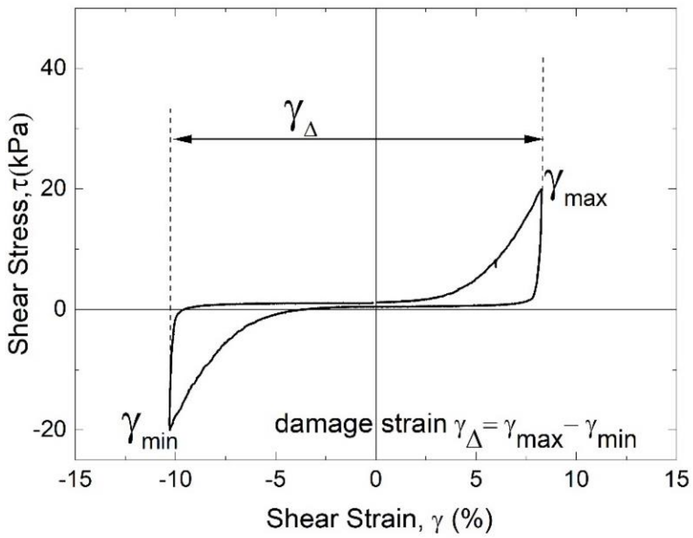

Figure 5. Schematic representation of damage strain

TEST RESULTS AND DISCUSSIONS

Effect of damage strain on post-liquefaction behavior

In this section post-liquefaction behavior of silica sand and Toyoura sand is discussed in term of stress-strain relationship, development of excess pore water pressure (EPWP) with shear strain, and variation of deviator stress (σ_d=σ_v-σ_h) with shear strain.

Figure 6 shows the post-liquefaction (undrained monotonic loading, ML) stress-strain response of sands with damage strain (γ_Δ) of 0~26%. As demonstrated in Figure 6 (a), and (b), the γ_Δ has significant effect on the peak undrained shear strength of silica sand and Toyoura sand. In this study peak undrained shear strength is the shear strength corresponding to the limiting shear strain ($\gamma_{L,SA}$), According to Kiyota et al.[10] the $\gamma_{L,SA}$ is the strain level at which strain localization initiates and specimen exhibits non-uniform behavior. The maximum value of peak undrained shear strength was obtained in the sample of silica sand without γ_Δ i.e. 195 kPa, reduced to 80 kPa with γ_Δ = 26 %. While similar undrained shear strength degradation behavior has been observed in Toyoura sand as shown in Figure 6(b), peak undrained shear strength reduced from 201kPa to 84kPa by increasing γ_Δ from 0% to 26%. The reduction in the value of peak shear strength during undrained ML can be associated with the strain-induced softening in the sand.

Figure 7 shows the development of excess pore water pressure (EPWP) with increment in shear strain level during undrained ML and each curve is marked with the γ_Δ. It can be observed that the minimum value of the EPWP increased from -197 kPa to -35.4 kPa with increase in the γ_Δ from 0 to 26% in case of silica sand (Figure 7(a)), while in the Toyoura sand the minimum value of the EPWP increased from -211kPa to 31kPa (Figure 7(b)).

Both the cyclic and monotonic loadings in this study were started under isotropic stress condition (σ_v' = σ_h') and the height of the specimen was kept constant during cyclic and post-cyclic ML. Therefore, any change in the value of deviator stress (σ_d=σ_v-σ_h) indicates a positive or negative dilatancy. Figure 8 shows the variation of σ_d with the increment in shear strain during undrained ML and each curve is marked with the γ_Δ. Figure 8 (a) and (b) shows that in both sand materials the value of σ_d increased up to peak value after which it drops suddenly. According to Kiyota et al.[10] this sudden drop of σ_d suggests the initiation of strain localization in sand. They also suggested that after $\gamma_{L,SA}$, specimen deformation is greatly influenced by the non-uniformities in the specimen. The test results in Figure 8 depicts the effect of damage strain (γ_Δ) on the peak value of σ_d and corresponding limiting shear strain ($\gamma_{L,SA}$)values. Figure 8 (a) shows increase in the $\gamma_{L,SA}$ and reduction in peak deviator stress (σ_d) with increase in the amplitude of γ_Δ from 0 to 26%, while Figure 8 (b) shows similar trend in Toyoura sand behavior. The trend in both sands suggests that the increase in the γ_Δ resulted in the reduction in the degree of dilatancy.

Relationship between $\gamma_{L,SA}$ and γ_Δ is shown in Figure 9, $\gamma_{L,SA}$ increases with increase in γ_Δ from 0 to 26%. Two observations can be made from Figure 8 and Figure 9, firstly the reduction in σ_d is associated with the softening induced by the γ_Δ. Secondly, the increase in limiting strain value indicates that strain localization in specimen is delayed by γ_Δ.

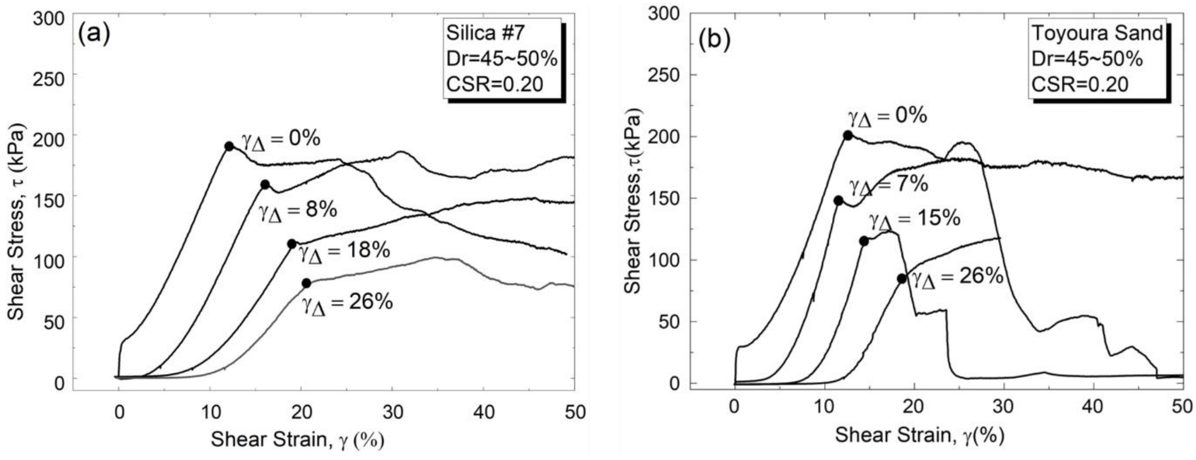

Figure 6 Post-liquefaction stress-strain response of sand in medium dense state (Dr=47±3) for various shear strain level**.** (a) Silica #7 (b) Toyoura sand

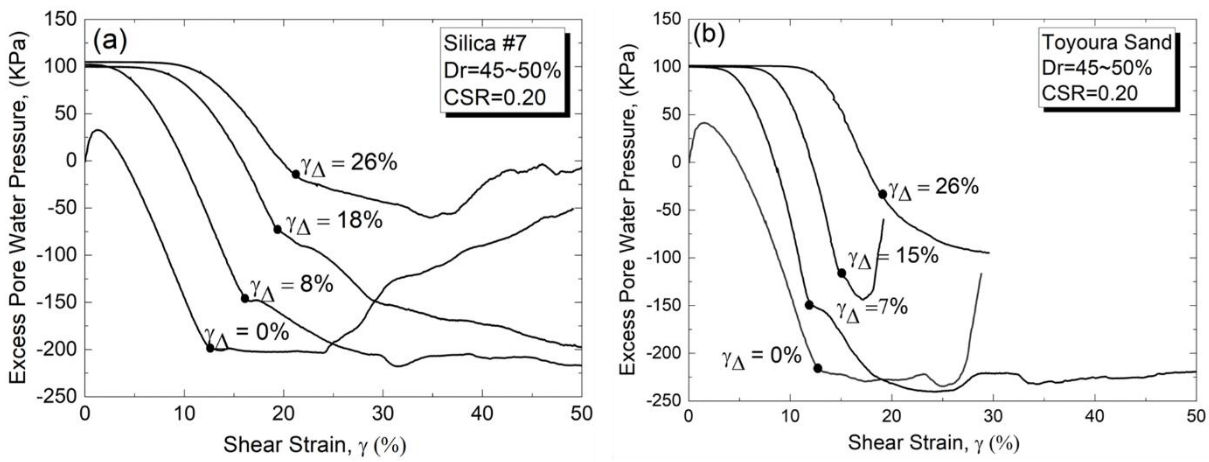

Figure 7 Post-liquefaction EPWP response of sand in medium dense state (Dr=47±3) for various shear strain level**.** (a) Silica #7 (b) Toyoura sand

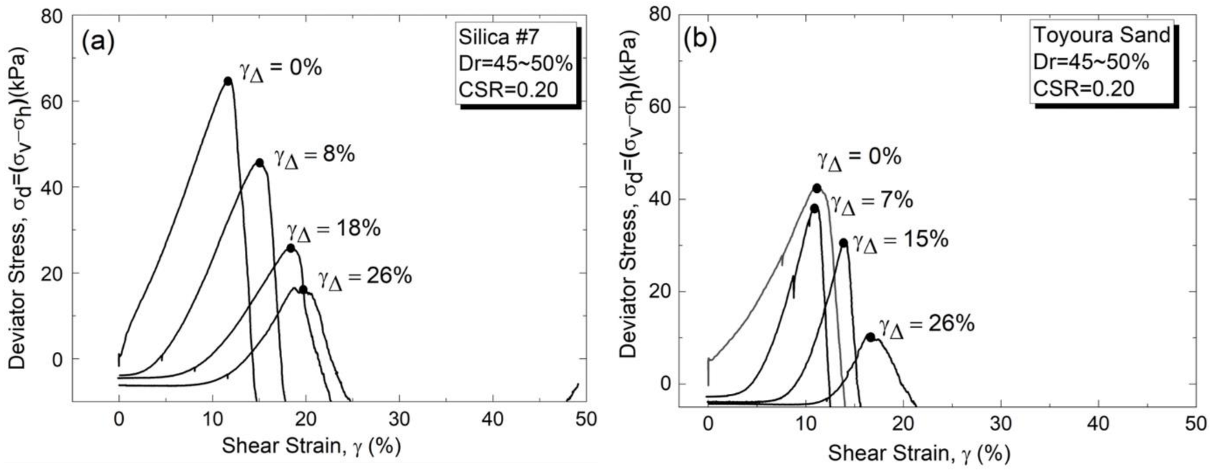

Figure 8 Post-liquefaction Deviator stress -strain response of sand in medium dense state (Dr=47±3) for various shear strain level**.** (a) Silica #7 (b) Toyoura sand

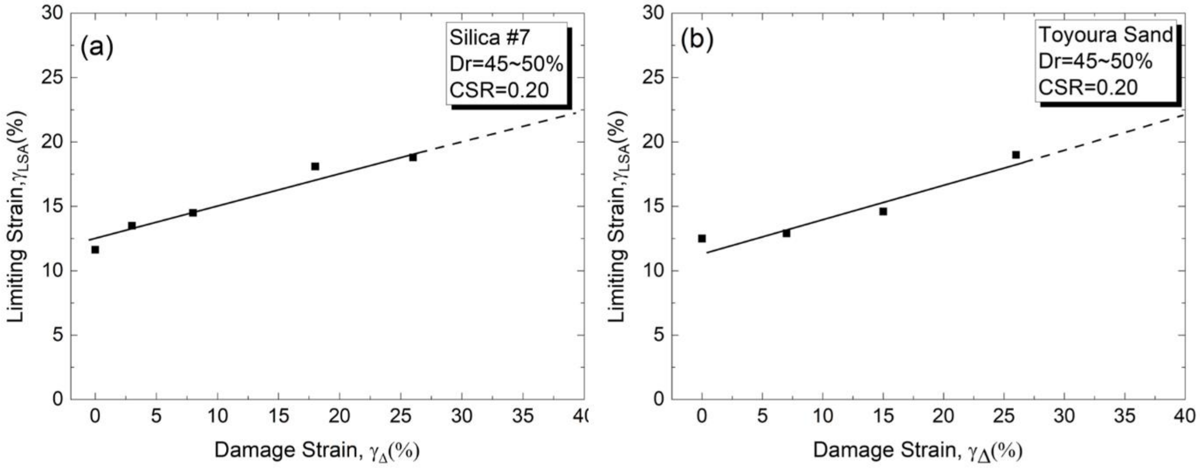

Figure 9 Rrelationship between limiting strain and damage strain (a) Silica #7 (b) Toyoura sand

Effect of damage strain on critical state line (CSL)

Effect of damage srain (γ_{Δ}) on the inclination of CSL is discussed in this section. Figure 10 illustrates the effective stress path of silica sand subjected to various γ_{Δ} levels. Figure 10 (a), (b) and (c) shows the effctive stress path with γ_{Δ}=0%, 8%, and 18% respectively. It was observed that the inclination of CSL decreased slightly with increase in γ_{Δ}. However, the phase transformation line (PTL) inclination remained unaffected by the γ_{Δ}. While same trend is followed by the Toyoura sand as shown in Figure 11 (a), (b), and (c). The result in this section depicts that though the increase in γ_{Δ} reduces the peak undrained shear strength.

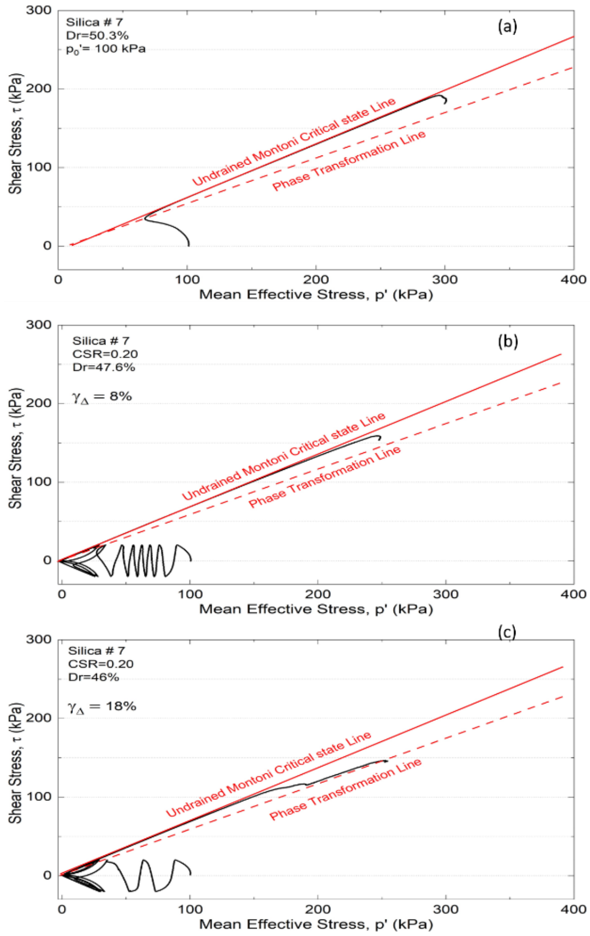

Figure 10 Silica sand stress path showing the CSL at γ_{Δ}=0,8, and 18%

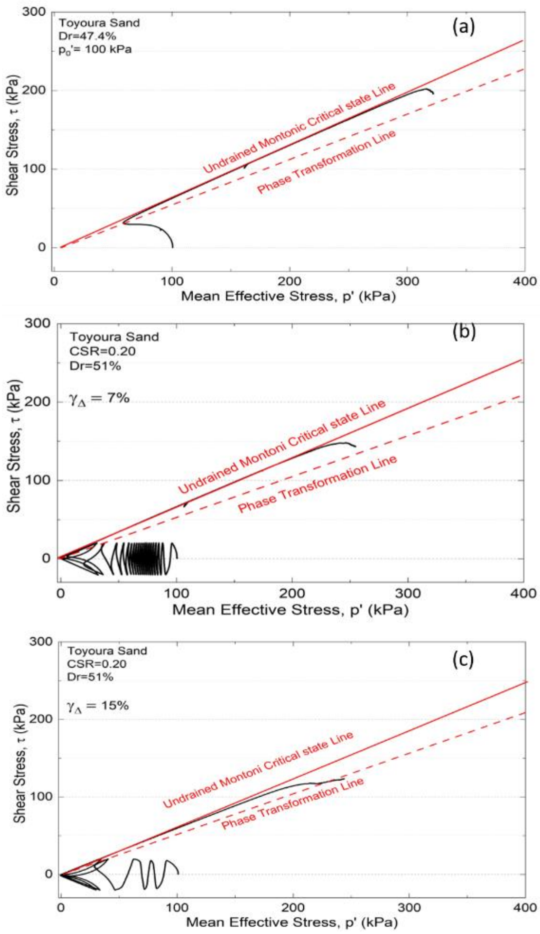

Figure 11 Toyoura sand stress path showing the CSL at γ_{Δ}=0,7, and 15%

Relationship between Strength degradation ratio and damage strain

To quantify the strength degradation due to the damage strain (γ_{Δ}), undrained strength degradation ratio (τ_d) and excess pore water pressure degradation ratio (r_d) are discussed in this section. The undrained strength degradation ratio (τ_d) is defined as the ratio of the undrained peak shear strength with γ_{Δ} ($\tau_{PL\Delta}$) to undrained peak shear strength without γ_{Δ} (τ_{PL}). The r_d is the ratio of minimum peak of EPWP in undrained monotonic loading with γ_{Δ} (ΔU_{Cyc}) to minimum peak of EPWP in undrained monotonic loading without γ_{Δ} (ΔU). For soils without degradation, τ_d and r_d are equal to 1.0, and less than 1.0 will indicate the degree of deterioration in reference to the monotonic loading test without γ_{Δ}.
Figure 12 shows relationship between τ_d and γ_{Δ}, there exists a linear correlation between τ_d and γ_{Δ} for both silica sand and Toyoura sand. Also, the correlation in Figure 12 (a) and (b) suggests that the $\tau_{PL\Delta}$ degraded to 60% of the original strength when γ_{Δ}=26%.

Figure 13 shows the relationship between excess pore water pressure degradation ratio (r_d) and damage strain (γ_{Δ}). The correlation depicts the influence of γ_{Δ} on the depletion of EPWP. The minimum peak of EPWP in silica sand reduced prominently up to 90% and 80% for silica sand and Toyoura sand respectively with the increase in γ_{Δ} up to 26%.

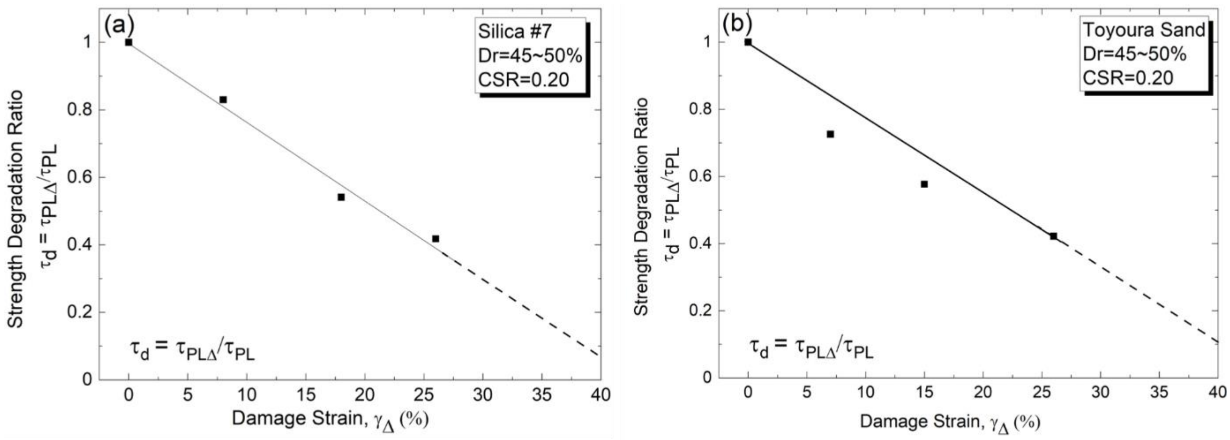

Figure 12 Strength degradation ratio versus damage strain (a) Silica #7 (b) Toyoura sand

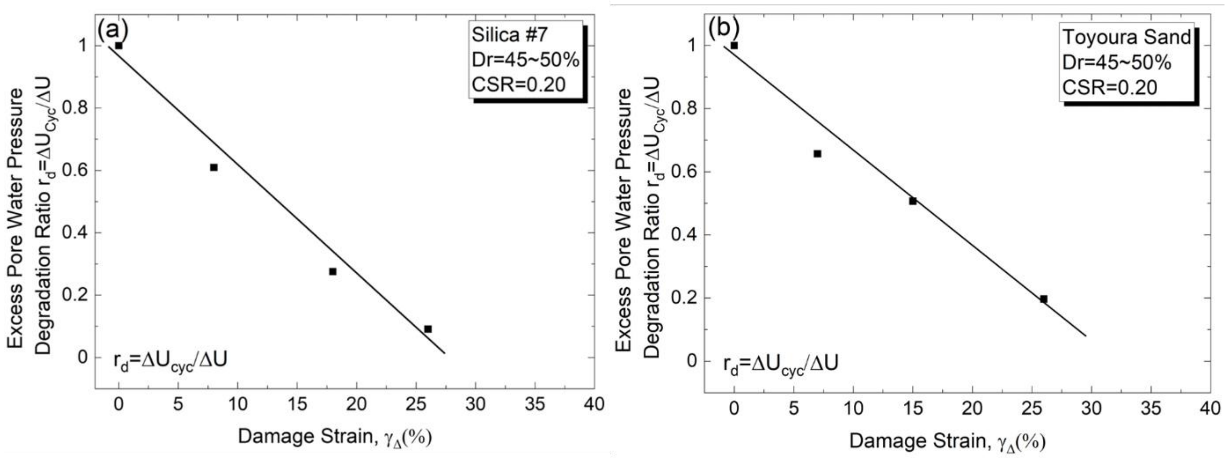

Figure 13 Excess pore pressure degradation ratio versus damage strain (a) Silica #7 (b) Toyoura sand

CONCLUSIONS

Post-cyclic undrained behavior of silica sand and Toyoura sand was investigated in this study, the focus of the study was to investigate the influence of damage strain (γ_Δ) on the post-cyclic peak undrained shear strength of two clean sands with comparable mean grain size and distribution. Both monotonic and multistage tests were performed using modified torsional shear apparatus, and the following conclusions were derived from the test results.

1) It was observed that γ_Δ has detrimental effect on the undrained peak shear strength, by inducing $\gamma_\Delta = 26\%$ the value of undrained peak shear strength reduced up to 60% of original strength. It shows that γ_Δ induces softening in the sand.
2) The peak value of deviator stress (σ_d) reduced with the increment in the γ_Δ, the trend in both sands suggests that the increase in the γ_Δ resulted in the reduction in the degree of dilatancy.
3) The increase in limiting strain value indicates that strain localization in specimen is delayed by increasing γ_Δ.
4) Critical State Line (CSL) inclination declined slightly with increase in γ_Δ.
5) Linear correlation is established between undrained strength degradation ratio ($\boldsymbol{\tau}_d$) and γ_Δ for both silica and Toyoura sand. Also, the correlation suggests that the $\boldsymbol{\tau}_{PL\Delta}$ degradation increases

with increase in damage strain (γ_Δ) level.

6) Relationship between excess pore water pressure degradation ratio (r_d) and γ_Δ suggests that, linear correlation exist between $\boldsymbol{\tau}_d$ and γ_Δ.

REFERENCES

1) Rouholamin, M., Bhattacharya, S., & Orense, R. P. (2017). Effect of initial relative density on the post liquefaction behaviour of sand. *Soil Dynamics and Earthquake Engineering*, *97*(March), 25–36. https://doi.org/10.1016/j.soildyn.2017.02.007
2) Seed, H.B., Lee, K.L., Idriss, I.M. and Makadisi, F.I. [1975]: The Slides in the San Fernando Dams during the Earthquake of February 9, 1971 – ASCE, J of the Geotechnical Engineering Division, GT7, pp. 651-688.
3) *Japan Rural Development Bureau*. (2012). On the revision of earth fill dam design codes, Japan Ministry of Agriculture, Forestry and Fisheries. October 2012, Doc. No.4, 13p. (in Japanese).
4) Tanaka, T., Tatsuoka, F. & Mohri, Y. (2012). Earthquake-induced failure of Fujinuma Dam, *Proc. Int.Symp. On Dams for a Changing World*, 24th Congress ICOLD, Kyoto, 6.47-6.52.
5) Duttine, A., Tatsuoka, F., Shinbo, T., & Mohri, Y. (2018). A new simplified seismic stability analysis taking into account degradation of soil undrained stress-strain properties and effects of compaction. *Validation of Dynamic Analyses of Dams and Their Equipment - Edited Contributions to the International Symposium on the Qualification of Dynamic Analyses of Dams and Their Equipments, 2016*, 215–234.
6) Tatsuoka, f., Koseki, j., & Takahashi, a. (2017). earthquake-induced damage to earth structures and proposal for revision of their design policy—based on a case history of the 2011 Off the Pacific Coast of Tohoku earthquake— *Journal of JSCE*, *5*(1), 101–112.
7) Seed, H. B. (1979). Soil liquefaction and cyclic mobility evaluation for level ground during earthquakes, *Journal of the Geotechnical Engineering Division,ASCE, 105(GT2),* 201–255.
8) Vaid, Y. P., & Thomas, J. (1995). Liquefaction and postliquefaction behavior of sand. *Journal of Geotechnical Engineering*, *121*(2), 163–173.
9) Yasuda, S., Yoshida, N., & Masuda, T. (1995). Stress-strain relationships of liquefied sands. *Earthquake Geotechnical Engineering.* 811-816.
10) Shamoto, Y., Zhang, J.-M., & Goto, S. (1996). A new Approach To Evalusate Post-Liquefaction deformation in saturated sand. In *11 World Conference on Earthquake Engineering*.
11) Kiyota, T., Sato, T., Koseki, J., & Abadimarand, M. (2008). Behavior of liquefied sands under extremely large strain levels in cyclic torsional shear tests. *Soils and Foundations*, *48*(5), 727–739.
12) Chiaro, G., Kiyota, T., & Koseki, J. (2013). Strain localization characteristics of loose saturated Toyoura sand in undrained cyclic torsional shear tests with initial static shear. *Soils and Foundations*, *53*(1), 23–34. https://doi.org/10.1016/j.sandf.2012.07.016
13) Ampadu, S.I.K. (1991). Undrained behavior of kaolin in torsional simple shear, *Ph.D. Thesis, Department of Civil Engineering, University of Tokyo, Japan*.
14) Yasuda S, Masuda T, Yoshida N, Nagase H, Kiku H, Itafuji S, Mine K, Sata K (1994) Torsional shear and triaxial compression tests on deformation characters of sands before and after liquefaction. In: Proceedings, 5th US-Japan workshop on earthquake resistant design of lifelines and countermeasures against soil liquefaction, pp 249–265