EFFECT OF VERTICAL CYCLIC LOADING HISTORY ON LIQUEFACTION PROPERTIES OF SANDY SOILS IN LARGE STRAIN TORSIONAL SHEAR TESTS

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ABSTRACT: In order to investigate the effect of vertical cyclic loading history on liquefaction characteristics of sandy soils, a series of undrained cyclic torsional shear tests was conducted on Toyoura sand and boiled sand that was retrieved at Urayasu City. Before the undrained cyclic torsional shear tests, initial shear moduli of the specimens were measured by dynamic and static measurements. It was found that the initial shear moduli and liquefaction resistance of both samples were increased as the number of drained vertical cyclic loadings increases without significant volume change, which may indicate that the inter-locking effect was enhanced by the vertical cyclic loading history. However, the test results showed the different tendency in large strain liquefaction behavior between Toyoura sand and boiled sand which have different fines content. The limiting value of shear strain to cause strain localization which would correspond to the maximum liquefaction-induced ground deformation of Toyoura sand became smaller by the vertical cyclic loading history, while the influence of such loading history on the limiting value of boiled sand was not clear.

Key Words: Liquefaction, torsional shear test, vertical loading history

INTRODUCTION

In the Kanto region, significant liquefaction occurred in the young reclamation land of Tokyo Bay and Tone River basin areas by the 2011 off the Pacific coast of Tōhoku Earthquake. One of the most affected areas by liquefaction was Urayasu city in Chiba Prefecture. A number of residential houses in Urayasu City suffered serious differential settlement which could cause an inconvenient life including the disconnection of buried lifelines. On the other hand, the occurrence of liquefaction was limited in the natural deposits. In addition, liquefaction damage in the old reclaimed lands was also limited compared with the young reclaimed lands.

Kyokawa et al. (2012) reported that the difference of damage aspects observed in the young and old reclaimed lands was due to the difference in their aging effect which the liquefaction resistance increases as time advances. Kiyota et al. (2009) investigated the aging effects on the liquefaction characteristics by using the in-situ frozen sample that were taken from Holocene and Pleistocene deposits. They suggested that the aging effects would be considered as a combination of cementation and inter-locking effects acting between the soil particles and these effects can be weakened by the process of liquefaction. Kiyota et al. (2011) also reported that the inter-locking effect was closely related to the small strain shear moduli. They showed that both small strain shear moduli and liquefaction resistance of the reconstituted samples increased due to the drained cyclic shear loading

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history before the liquefaction test.

Here, we considered that the aging effect of the young reclaimed land is caused only by the inter-locking effect which would be enhanced by the change in the vertical stress resulted by the seasonal change of the ground water level. In this study, therefore, in order to investigate the influence of vertical cyclic loading history on the liquefaction characteristics of sandy soils, a series of undrained cyclic torsional shear tests was performed.

TEST MATERIALS, APPARATUS AND METHODOLOGY

Test materials

The test materials used in this study were Toyoura sand and the boiled sand which was taken from the reclaimed land in Urayasu City affected by liquefaction in the 2011 off the Pacific coast of Tōhoku Earthquake. Figure 1 shows the particle size distribution of the Toyoura sand and Urayasu boiled sand. The fines content and uniformity coefficient of the Urayasu boiled sand is higher than those of Toyoura sand. It should be noted that both Toyoura sand and Urayasu boiled sand have no plasticity. Basic properties of the tested materials are summarized in Table 1.

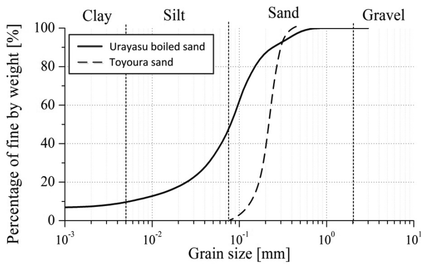

Figure 1. Particle size distribution

Table 1. Basic properties of tested materials

Materials	D_{50}(mm)	F_c(%)	U_c	e_{max}	e_{min}	G_s
Urayasu boiled sand	0.079	30.5	17.5	1.261	0.683	2.683
Toyoura sand	0.204	0.1	1.6	0.975	0.561	2.635

Apparatus and methodology

Figure 2 shows the torsional shear apparatus used in this study. The apparatus was modified to enlarge the double amplitude torsional shear strain levels exceeding 100%, while the specimen height was 30 cm. The outer and inner diameters of the specimen were 15 and 9 cm, respectively. Refer to Koseki et al. (2005) for the details of the stress computations. A thickness of membrane used was 0.3mm. The vertical deformation of the specimen was measured by using a displacement gauge. The effective stress and the volume change of the specimen during the isotropic consolidation and drained cyclic loading were measured by using differential pressure gauges.

After saturating the specimens, they were consolidated to an isotropic effective stress, σ'_m of 50 kPa which is almost equivalent to the in-situ overburden stress at the depth where liquefaction could occur at the sampling site of Urayasu boiled sand, with a back pressure of 200 kPa. After the isotropic consolidation, some specimens were subjected to 100 or 1000 cycles of vertical loading with stress amplitudes of ± 5 kPa (σ'_z = 45~55 kPa) under drained condition. This procedure was conducted to develop the aging effects on the specimen in the laboratory.

The strain shear moduli were dynamically measured for some specimens immediately before the undrained cyclic torsional shear tests by using a pair of accelerometers to measure the arrival of S wave at two different heights on the side surface of the specimen as shown in Fig. 3. From the S wave velocity, V_s, as formulated in Fig. 3, the dynamic shear moduli, G_d, were evaluated as $G_d = \rho V_s^2$, where ρ is mass density of the specimen.

The statically measured vertical Young's modulus, E_v, was calculated from the slope of the axial strain, ε_v, and deviator stress, q, during the drained cyclic loading as shown in Fig. 4. When the specimen is assumed to be an isotropic elastic body, it can be converted to static shear moduli, G_s (= $E_v/(2(1+\nu))$. The effects of stress state-induced anisotropy should be considered with converting G_s into E_v (Tsutsumi et al., 2006). Considering the measurement of G_s in this study, it was given the same stress amplitude and the same confining pressure for the qualitative comparisons between samples, therefore, the effects of anisotropy was not considered in this study. Poisson's ratio, ν, was set to 0.17 based on the test results of Toyoura sand (Hoque et al., 1996).

After the above procedures, undrained cyclic torsional shear tests (liquefaction tests) were conducted with constant amplitude of cyclic shear stress, τ_d/σ'_m. All the test conditions were shown in Table 2.

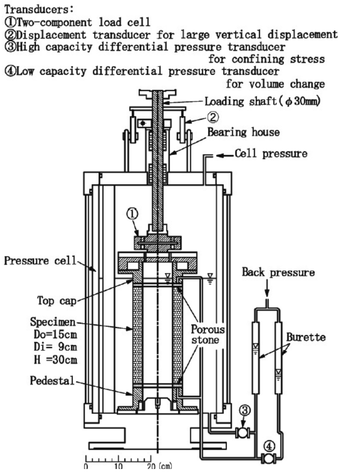

Figure 2. Torsional shear test apparatus

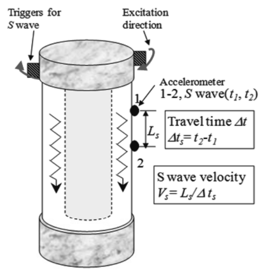

Figure 3. Diagram of S wave triggers and accelerometers

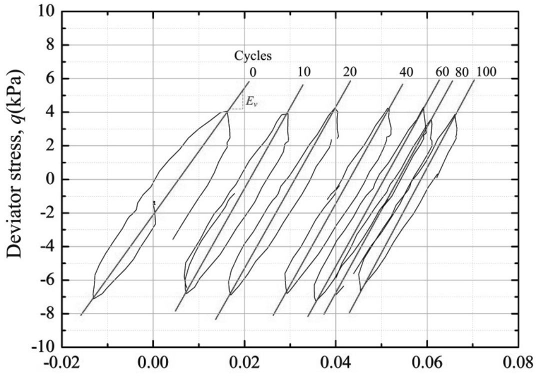

Figure 4. Relationship between deviator stress and axial strain during drained vertical cyclic loading before liquefaction test

Table 2. Test conditions

No.	Materials	Stress ratio (τ_d/σ'_m)	Number of Drained cycles (loading history)	D_r		Limiting value of shear strain (single amp.), $\gamma_{L(SA)}$
				Before vertical cyclic loading	After vertical cyclic loading (before liquefaction test)	
Ura-0-0.12	Urayasu	0.12	0	30.5%	-	26.5%
Ura-0-0.14	Urayasu	0.14	0	37.1%	-	21.7%
Ura-0-0.15	Urayasu	0.15	0	36.6%	-	-
Ura-0-0.20	Urayasu	0.2	0	32.2%	-	24.0%
Ura-100-0.12	Urayasu	0.12	100	29.4%	30.0%	23.5%
Ura-100-0.14	Urayasu	0.14	100	40.0%	40.3%	32.9%
Ura-100-0.20	Urayasu	0.2	100	34.0%	34.6%	28.7%
Ura-1000-0.20	Urayasu	0.2	1000	39.9%	43.5%	35.5%
Toyo-0-0.16	Toyoura	0.16	0	32.6%	-	-
Toyo-0-0.20	Toyoura	0.2	0	32.9%	-	33.3%
Toyo-100-0.16	Toyoura	0.16	100	20.8%	21.2%	-
Toyo-100-0.20	Toyoura	0.2	100	40.7%	40.7%	19.7%

TEST RESULTS

Shear moduli before liquefaction test

As mentioned at previous chapter, G_d and G_s were investigated before conducting undrained cyclic torsional shear tests. The following function proposed by Hardin and Richart (1963) was used in this study to normalize the effect of void ratio, e.

$$f(e) = (2.17-e)^2/(1+e) \tag{2}$$

Figures 5 and 6 show the relationships between the number of drained vertical cyclic loadings, N_c, and normalized dynamic shear moduli ($G_d/f(e)$ and $G_d/f(e)$ / $G_d/f(e)_{\text{no-loading}}$) for the Urayasu boiled sand. It was found that as the number of drained vertical cyclic loadings, N_c, increases, the value of $G_d/f(e)$ / $G_d/f(e)_{\text{no-loading}}$ increases. This feature implies that the boiled sand specimen could be strengthened by the enhanced inter-locking between the soil particles due to drained vertical cyclic loading. However, the result of Ura-100-0.14 that the G_d was measured at 20 cycles intervals indicates that the value of G_d becomes stable when the cyclic loading number exceeds 60 as shown in Fig. 6.

Figures 7 and 8 show the relationships between N_c and normalized static shear moduli ($G_s/f(e)$ and $G_s/f(e)$ / $G_s/f(e)_{\text{no-loading}}$) by static measurement for Toyoura sand and boiled sand. The increases in the G_s of Toyoura sand which was higher than Urayasu boiled sand were observed by applying drained vertical cyclic loadings, except for the result of Ura-100-0.12 which may be caused by sample variation.

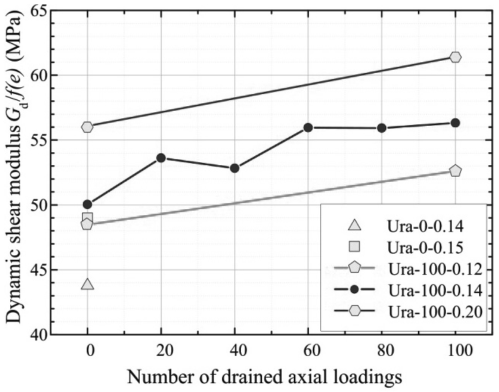

Figure 5. Relationship between $G_d/f(e)$ and number of drained vertical cyclic loading, N_c

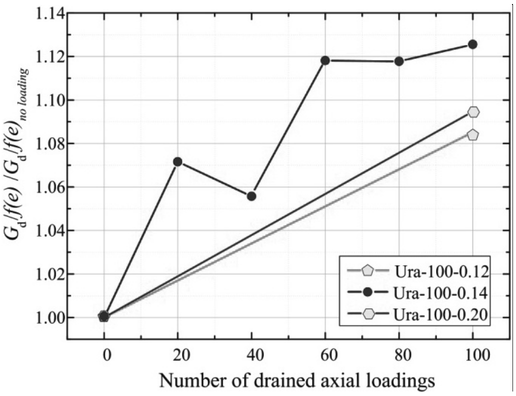

Figure 6. Relationship between $G_d/f(e)$ / $G_d/f(e)_{\text{no loading}}$ and number of drained vertical cyclic loading, N_c

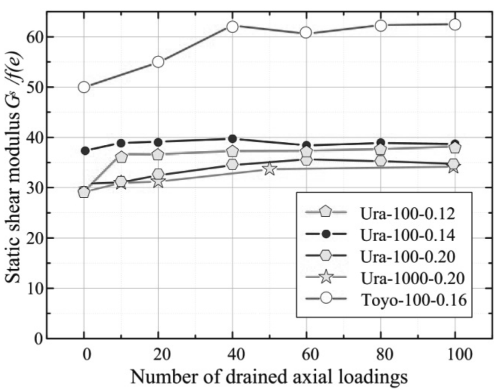

Figure 7. Relationship between $G_s/f(e)$ and number of drained vertical cyclic loading, N_c

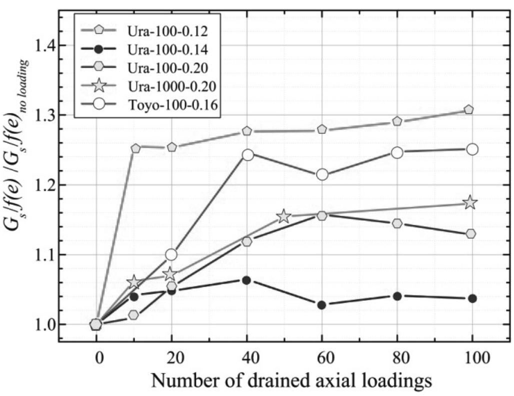

Figure 8. Relationship between $G_s/f(e)$ / $G_s/f(e)_{\text{no loading}}$ and number of drained vertical cyclic loading, N_c

Liquefaction properties

Typical liquefaction test results of Urayasu boiled sand were shown in Figs. 9, 10 and 11. The cyclic mobility was observed where the effective stress was recovered repeatedly after showing almost zero effective stress state. As indicated on the stress-paths shown in these figures, the liquefaction processes of the specimens having different vertical cyclic loading histories were different from each other irrespective of the same τ_d/σ_m' and the similar D_r. The extent of the reduction rate of effective stress of the specimens having 100 and 1000 vertical cyclic loading histories was much smaller than that of the one without vertical cyclic loading history.

Test results of Toyoura sand specimens with/without the drained vertical loading history were shown in Figs. 12 and 13. As compared to Figs 9 and 10, Toyoura sand seems to have higher liquefaction resistance than that of Urayasu boiled sand even their D_r were similar to each other.

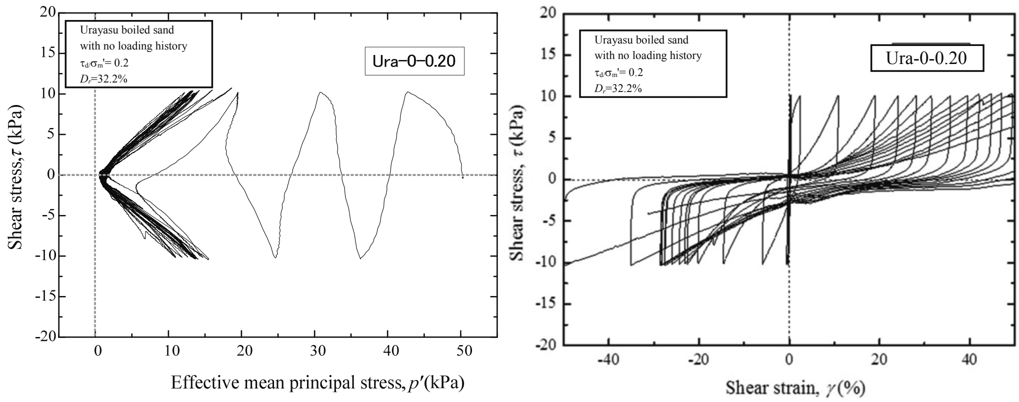

Figure 9. a) Effective stress path and b) stress-strain relation of Urayasu boiled sand without drained vertical cyclic loading history

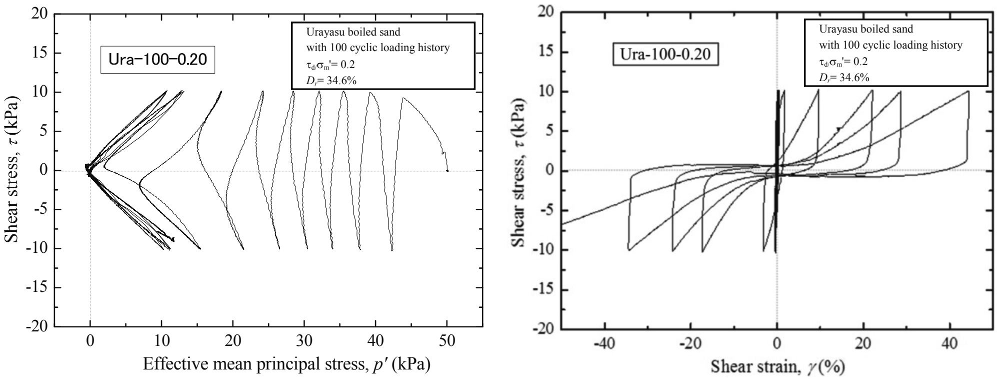

Figure 10. a) Effective stress path and b) stress-strain relation of Urayasu boiled sand with 100 drained vertical cyclic loading history

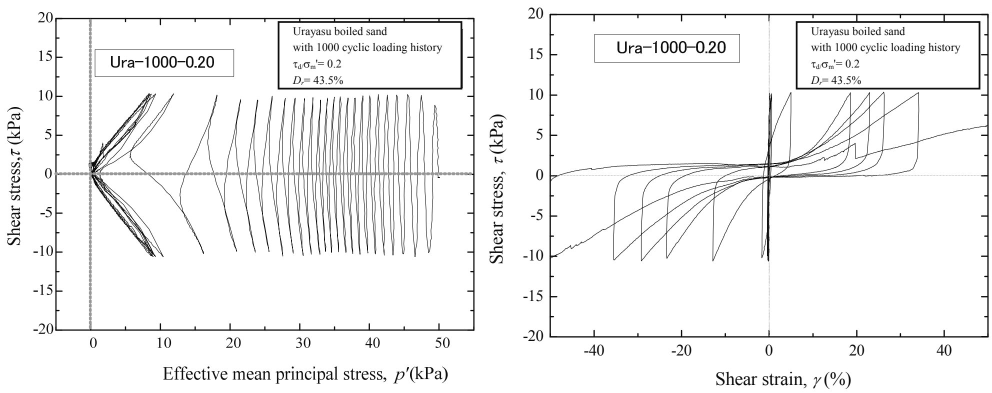

Figure 11. a) Effective stress path and b) stress-strain relation of Urayasu boiled sand with 1000 drained vertical cyclic loading history

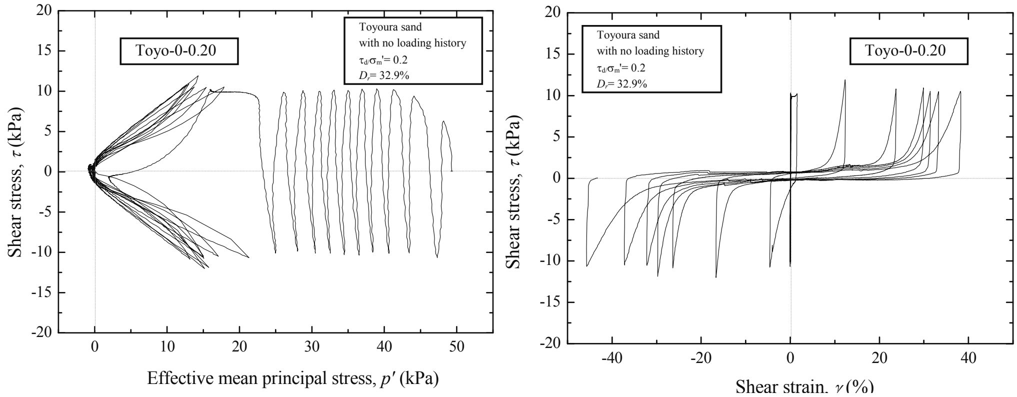

Figure 12. a) Effective stress path and b) stress-strain relation of Toyoura sand without drained vertical cyclic loading history

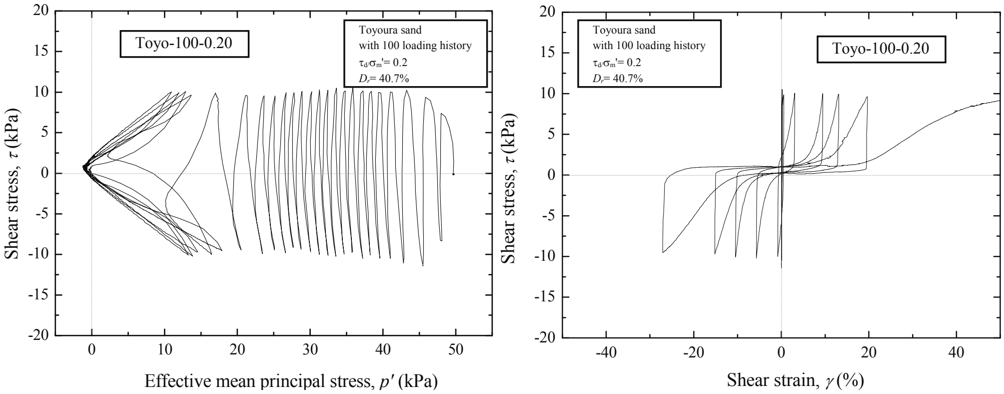

Figure 13. a) Effective stress path and b) stress-strain relation of Toyoura sand with 100 drained vertical cyclic loading history

Figure 14 shows the relationship between τ_d/σ'_m, and N_c required to cause double amplitude shear strain, $\gamma_{(DA)}$= 7.5%, 15% and 30% of Urayasu boiled sand and Toyoura sand. It was found that, under the same shear stress ratio, the liquefaction resistances of both Toyoura sand and Urayasu boiled sand increase due to the increase of cycles of vertical loading history. The difference in the liquefaction resistance curves between $\gamma_{(DA)}$= 7.5 %, 15 % and 30 % was small for all specimens which would imply that the large deformation was induced suddenly when the specimens were liquefied. The details of Fig. 14 were summarized in Table 3.

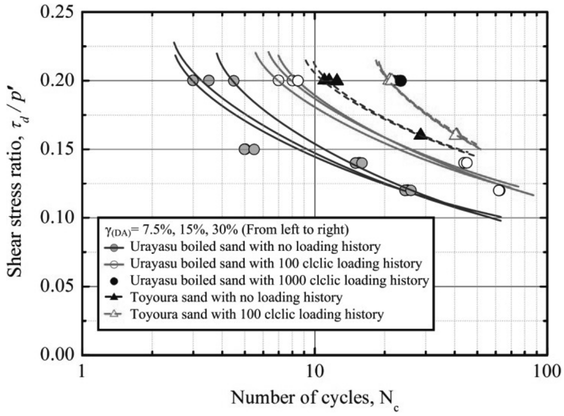

Figure 14. Shear stress ratios required to cause double amplitude shear strain of 7.5%, 15% and 30%

Table 3. Number of cycles of a given shear strain amplitude

No.	D_r	Cycles (loading history)	Stress ratio τ_d/σ'_m	Number of cycles (liquefaction test)				
				$\gamma_{(DA)}$ 3%	$\gamma_{(DA)}$ 7.5%	$\gamma_{(DA)}$ 15%	$\gamma_{(DA)}$ 30%	$\gamma_{(DA)}$ 60%
Ura-0-0.12	30.5%	0	0.12	24	24.5	25	26	29.5
Ura-0-0.14	37.1%	0	0.14	14.5	15	15.5	16	19
Ura-0-0.15	36.6%	0	0.15	4.5	5	5	5.5	-
Ura-0-0.20	32.2%	0	0.2	2.5	3	3.5	4.5	9
Ura-100-0.12	30.0%	100	0.12	61	61.5	62	62	63.5
Ura-100-0.14	40.3%	100	0.14	43	43.5	44.5	45	46.5
Ura-100-0.20	34.6%	100	0.20	7	7.5	8	8.5	10
Ura-1000-0.20	43.5%	1000	0.20	22.5	23	23	23.5	26
Toyo-0-0.16	32.6%	0	0.16	28	28.5	28.5	-	-
Toyo-0-0.20	32.9%	0	0.2	11	11.5	11.5	12.5	14.5
Toyo-100-0.16	21.2%	100	0.16	31	31.5	31.5	32	-
Toyo-100-0.20	40.7%	100	0.2	22	22.5	22.5	23	-

Limiting value of shear strain to cause strain localization

In the present tests, the $\gamma_{(DA)}$ values continued to increase and approached 100 % that is the capacity of the apparatus, irrespective of specimen densities. However, there is a limit to the liquefaction-induced ground deformation caused by the actual earthquake.

Kiyota et al. (2008) reported that the limiting shear strain to cause strain localization, γ_L, under undrained cyclic loading would possibly correspond to the liquefaction-induced maximum ground deformation. In fact, the non-uniform deformation or strain localization was observed at higher strain levels during the liquefaction tests in this study. However, since the initiation of strain localization could not be clearly defined based on the visual observation of the specimen deformation, it was defined based on the change in the response of the deviator stress, $q=\sigma'_v-\sigma'_h$, that was measured during the liquefaction tests while keeping the specimen height constant. Refer to Kiyota et al. (2008 and 2010) for the details of the definition of γ_L. In this study, the state at which the amplitude of q decreased suddenly was considered as the limiting state to initiate formation of shear band and thus strain localization as shown in Figs. 15 and 16.

The relationship between single amplitude of γ_L and D_r of the specimens was shown in Fig. 17, and the results are summarized in Table 2. The influence of vertical loading history on the γ_L of the boiled sand was not clear. The cases of Ura-0-0.12 and Ura-100-0.12 which have different loading history show similar γ_L. On the other hand, in the cases of Toyo-0-0.20 and Toyo-100-0.20, the effect of loading history which caused the γ_L to decrease was observed in Toyoura sand.

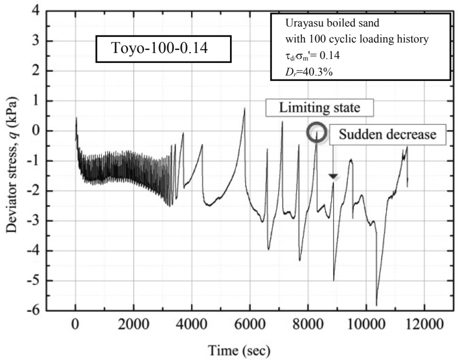

Figure 15. Time history of deviator stress

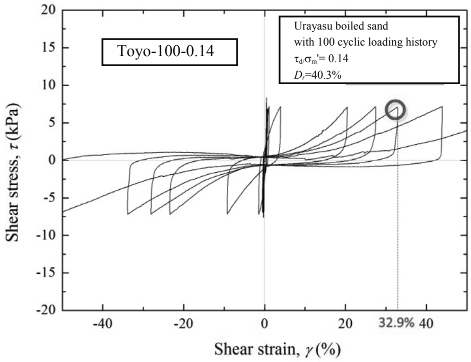

Figure 16. Stress-strain relation and limiting strain

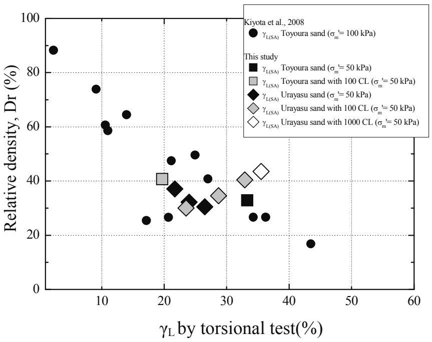

Figure 17. Relationship between limiting shear strain and relative density

CONCLUSIONS

In order to investigate the effect of drained vertical cyclic loading history on the liquefaction characteristics of sandy soils, a series of undrained cyclic torsional shear tests was performed on Toyoura sand and Urayasu boiled sand. The test results could be summarized as follows;

1. The increases in shear moduli due to applying drained vertical cyclic loading were observed. Since the densification of the specimen during the cyclic loading was negligible, the inter-locking between the soil particles was possibly enhanced due to the cyclic loading history. On the other hand, the increase rate of the shear moduli has diminished as the number of cyclic loading increased.
2. The effect of vertical loading history on the liquefaction resistance was investigated. It was found that the liquefaction resistance of both Toyoura sand and boiled sand increase due to the increase of drained cyclic loading history.
3. The effect of vertical cyclic loading history on the γ_L was also studied. A decrease in the γ_L value of Toyoura sand can be observed with an increase in the cycles of loading history, while the influence of such loading history on the γ_L value of boiled sand was not clear.

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