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LIQUEFACTION CHARACTERISTICS AND SMALL STRAIN SHEAR MODULI OF RECONSTITUTED URAYASU SAND IN TORSIONAL SHEAR TEST

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Abstract: One of the issues of liquefaction arising after the 2011 off the Pacific Coast of Tohoku Earthquake, Japan, is aging effects on liquefaction resistance of sandy deposits. The aging effects of sandy deposits are considered to be strengthening of micro-structure of soil particles through time, and they would be closely related to the small strain shear moduli. In this study, to investigate the relationship between the liquefaction resistance and the small strain shear moduli, undrained cyclic torsional shear tests and dynamic small strain shear moduli measurements were conducted on boiled silty sand which was retrieved in Urayasu city where significant liquefaction occurred in the 2011 earthquake. In order to artificially enhance the micro-structure of soil particles which would correspond to the aging effects, some specimens were subjected to drained cyclic vertical loading after isotropic consolidation. The small strain shear moduli of the specimens were increased by applying drained cyclic vertical loading, and larger liquefaction resistance was obtained with an increase in the small strain shear moduli. However, such enhanced initial soil structure has little direct effect on the large strain characteristics.

Introduction

The 2011 off Pacific Coast of Tohoku Earthquake with a Mw 9.0 hit Japan. This quake caused significant soil liquefaction over a wide range in the Kanto and the Tohoku Regions (Towhata et al., 2014; Yamaguchi et al., 2012; Tsukamoto et al., 2012). The occurrence of liquefaction has been observed in total 190 local cities, towns and villages, and a large number of liquefaction-induced damages to residential houses and buried lifelines were reported, especially in the Tokyo Bay area and in the downstream basin of Tone River (Editorial committee of Joint Survey Report on Great East Japan Earthquake, 2014). One of the most affected areas by liquefaction was Urayasu city in Chiba Prefecture. Damage to approximately 8,700 houses was found in Urayasu city, which could cause an inconvenient life including the disconnection of buried lifelines (e.g. Yasuda et al., 2012). On the other hand, in Urayasu city, the occurrence of liquefaction was limited in the natural deposit and old reclaimed areas as compared with the young reclaimed area.

Towhata, et al. (2014) among others reported that the difference of damage aspects between the young and old reclaimed areas was due to the difference in their aging effects which the liquefaction resistance would increase as time advances. This feature which the dynamic properties of sandy soils are not determined by the density alone have been referred to as: change in soil structure or fabric; induced anisotropy; and development of interlocking during which the soil particles have been subjected to substantial pressure and cyclic loading. The previous relevant works (e.g., Finn et al., 1970; Ishihara and Okada, 1978, Seed, 1979) indicated that such microscopic structure of sandy soils has a significant influence on the soil resistance to liquefaction. Furthermore, Tokimatsu and Hosaka (1986) reported that the soil structure was closely related to the small strain characteristics.

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Kiyota et al. (2009) investigated the aging effects on the liquefaction characteristics based on the small strain measurements in the triaxial apparatus. 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. In addition, Kiyota et al. (2011) showed that both small strain shear moduli and liquefaction resistance of the fine sandy soils which were taken from natural Holocene and Pleistocene deposits increased due to the drained cyclic torsional shear loading history before the liquefaction test.

In this study, in order to investigate the relationships between the aging effect, liquefaction resistance and small strain shear moduli, a series of undrained cyclic torsional shear tests and dynamic small strain measurements was conducted on boiled silty sand with a fines content of 30%, which was retrieved in Urayasu city after the 2011 earthquake. Since we considered that the aging effects of the sandy deposit in Urayasu city have been developed by the inter-locking effect, some specimens were subjected to drained cyclic vertical loading to enhance the soil structure as an artificial aging effect.

Test materials

The test material used in this study was boiled sand which was taken from the young reclaimed land in Urayasu City affected by liquefaction in the 2011 Off the Pacific Coast of Tōhoku Earthquake (called Urayasu sand hereafter). In addition, we used Toyoura sand which is fine sand with sub-angular particle shape for the purpose of comparison. Figure 1 shows the particle size distribution of the Urayasu sand and Toyoura sand. The fines content and uniformity coefficient of the Urayasu sand is higher than those of Toyoura sand. It should be noted that both Urayasu sand and Toyoura sand have no plasticity. Basic properties of the tested materials are summarized in Table 1.

The specimens were prepared by pluviating oven-dried sands through air, and the height of pluviation was changed to adjust the dry density at the target value of Dr 30-40%.

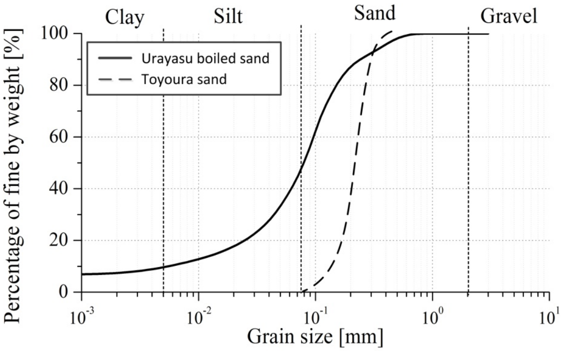

Figure 1. Particle size distribution of tested materials

Table 1. Basic properties of tested materials

Materials	D_{50}(mm)	F_c(%)	U_c	e_{max}	e_{min}	G_s
Urayasu 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

Hollow cylindrical torsional shear apparatus and methodology

Figures 2a) and b) 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 hollow cylindrical specimen were 15 and 9 cm, respectively. Refer to Kiyota et al. (2008) and Koseki et al. (2005) for the details of the modification of the apparatus and stress computations in the specimen. A thickness of membrane used was 0.3mm. The vertical and torsional displacement of the specimen was measured by using a vertical displacement gauge and a potentiometer, respectively. The effective stress and the volume change of the specimen during the tests were measured by differential pressure gauges.

After saturating the specimens, they were consolidated to an isotropic effective stress, σ'_m of 50 kPa which was assumed to be the in-situ overburden stress at the depth where liquefaction could occur at the sampling site of Urayasu 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'_v = 45~55 kPa) under drained condition. This procedure was conducted to develop the aging effects on the specimen in the laboratory, and it was also adopted by previous literatures (e.g., Tokimatsu and Hosaka, 1986) for the same purpose.

The small strain shear moduli, G_d, were dynamically measured for some specimens of Urayasu sand during drained cyclic loading that mentioned above and before the undrained cyclic torsional shear tests. A pair of the accelerometers received S wave at two different heights on the side surface of the specimen as shown in Fig. 2c). From the S wave velocity, V_s, as formulated in Fig. 2c), the dynamic shear moduli, G_d, were evaluated as $G_d = \rho V_s^2$, where ρ is mass density of the specimen. Unfortunately, the G_d were not measured for Toyoura sand, so that statically measured shear moduli, G_s, were used for the comparison with Urayasu sand.

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.

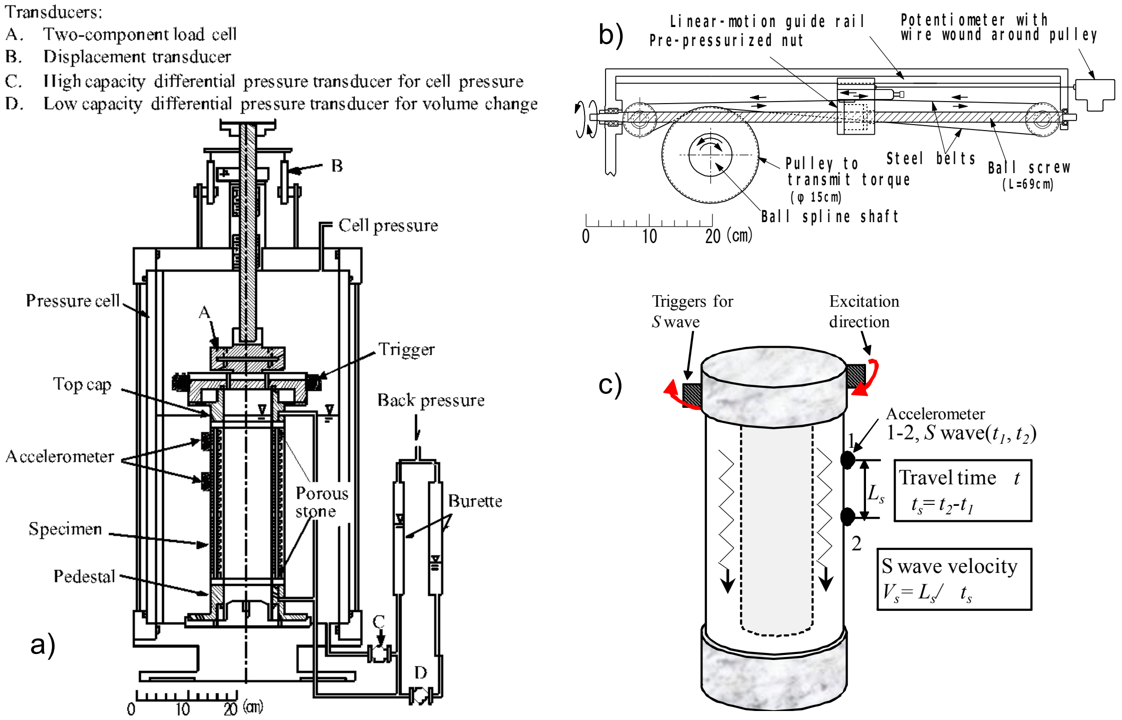

Figure 2. a) Torsional shear apparatus, b) plan view of torque-transmission part and c) Diagram of S wave triggers and accelerometers on a hollow cylindrical specimen (Kiyota et al., 2008 and 2013)

Table 2. Test condition in this study

No.	Materials	Stress ratio (τ_d/σ'_m)	Number of drained cycles (loading history)	Relative density of specimen, D_r, at s_m'= 50 kPa	
				Before vertical cyclic loading	After vertical cyclic loading (before liquefaction test)
U0-0.12	Urayasu	0.12	-	30.5%	-
U0-0.14	Urayasu	0.14	-	37.1%	-
U0-0.15	Urayasu	0.15	-	36.6%	-
U0-0.20	Urayasu	0.2	-	32.2%	-
U100-0.12	Urayasu	0.12	100	29.4%	30.0%
U100-0.14	Urayasu	0.14	100	40.0%	40.3%
U100-0.20	Urayasu	0.2	100	34.0%	34.6%
U1000-0.20	Urayasu	0.2	1000	39.9%	43.5%
T0-0.16	Toyoura	0.16	-	32.6%	-
T0-0.20	Toyoura	0.2	-	32.9%	-
T100-0.16	Toyoura	0.16	100	20.8%	21.2%
T100-0.20	Toyoura	0.2	100	40.7%	40.7%

Results and discussion

(1) Shear moduli during pre-vertical drained cyclic loading

The shear moduli, G_d, were measured dynamically before conducting undrained cyclic torsional shear tests. The values of G_d were normalized by the void ratio function for the effect of different void ratio (Hardin and Richart, 1963).

Figure 3 shows the relationship between the number of drained vertical cyclic loadings, N_c, and normalized dynamic shear moduli, G_d/f(e) for the Urayasu sand. The increase in the G_d/f(e) was observed by applying drained vertical cyclic loading. According to Table 2 in the previous section, the change in the value of D_r before and after the drained cyclic loading were almost negligible. These features imply that rather than a sample densification, the specimen of Urayasu sand could be strengthened with enhanced structure between the soil particles due to the drained cyclic loading.

Figure 4 shows the relationship between the N_c and ratio of dynamic shear moduli to those measured before cyclic loading, G_d/f(e)/G_{di}/f(e_i), for the Urayasu sand. The G_d values increased by about 10% after 100 drained cyclic loadings. The result of U100-0.14 that the G_d was measured at 20 cycle intervals indicates that increasing tendency of the G_d for Urayasu sand changed and became stable in the same degree when the N_c exceeded 60 cycles.

Figures 5 and 6 show the relationships between the N_c and normalized static shear moduli, G_s/f(e), and the N_c and ratio of static shear moduli to those measured before cyclic loading, G_s/f(e)/G_{si}/f(e_i) for Toyoura sand and Urayasu sand. Both the value and the increasing ratio of the G_s of Toyoura sand were lager than Urayasu sand. The G_s value of Toyoura sand after 100 drained cyclic loadings in Fig. 5 was almost equivalent to the G_d of Urayasu sand in Fig. 3. However, since the G_s was evaluated from the cyclic stress-strain relationships with a double amplitude vertical strain of approximately 0.02% and the strain level of the G_d was thought to be less than 0.001%, the small strain shear moduli of Toyoura sand should be larger than Urayasu sand if it would be measured.

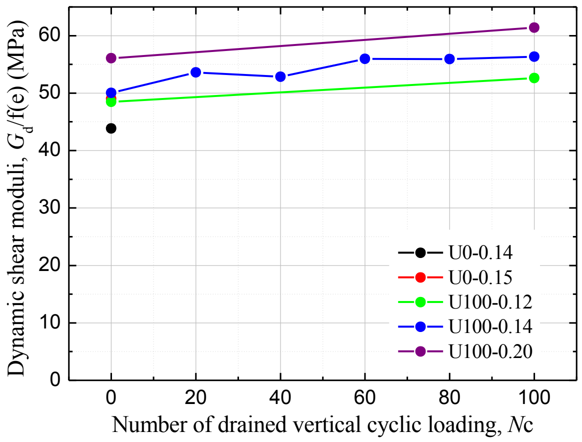

Figure 3 Relationship between G_d/f(e) and number of drained cyclic loading, N_c

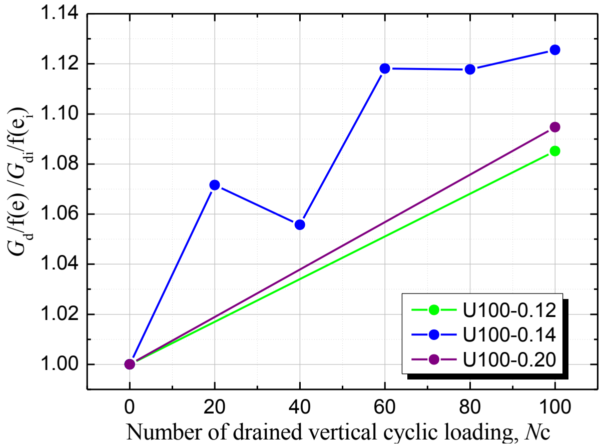

Figure 4 Relationship between G_d/f(e)/G_{di}/f(e_i) and number of drained cyclic loading, N_c

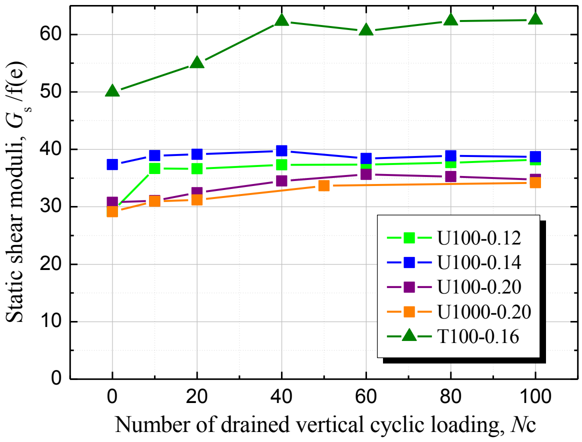

Figure 5 Relationship between G_s/f(e) and number of drained cyclic loading, N_c

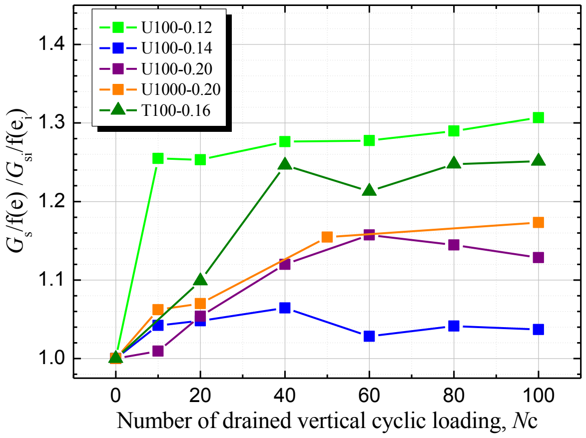

Figure 6. Relationship between G_s/f(e)/G_{si}/f(e_i) and number of drained cyclic loading, N_c

(2) Liquefaction characteristics

Typical liquefaction test results of Urayasu sand were shown in Figs. 7-9. 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 drained 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 with 100 and 1000 cyclic loading histories (Figs. 8 and 9) was much smaller than that without vertical cyclic loading history (Fig. 7).

Test results of Toyoura sand specimens with/without the drained vertical loading history were shown in Figs. 10 and 11. As compared to Figs. 7 and 8, Toyoura sand seems to have higher liquefaction resistance than that of Urayasu sand even their D_r were similar to each other.

Figure 12 shows the relationship between τ_d/σ'_m, and N_c required to cause double amplitude shear strain, $\gamma_{(DA)}$= 7.5% of Urayasu sand and Toyoura sand. It shows clearly that the liquefaction resistances of both Toyoura sand and Urayasu sand increase due to the increase of cycles of vertical loading history. This feature that drained small cyclic loading history caused specimen increase in shear stiffness without significant volume change as well as liquefaction resistance have been reported by previous literatures (Tokimatsu & Hosaka, 1986; Kiyota et al., 2009). However, the previous studies were investigated mostly with clean sands in triaxial apparatus. This study found the same tendency on silty boiled Urayasu sand with fines content of 30 %.

Meanwhile, the effects of drained cyclic loading history on large deformation characteristics after liquefaction may not be significant in the case of Urayasu sand. Figure 13 shows the relationship between N_c after excess pore water pressure ratio, $\Delta u/\sigma_m'$, exceed 95% and $\gamma_{(DA)}$. Note that the tested specimens in Fig. 13 were subjected to the same τ_d/σ_m' (=0.2). The $\gamma_{(DA)}$ increased to 40% in two cycles for Urayasu sand after the $\Delta u/\sigma_m'$ reached 95%, irrespective of the different number of drained cyclic loading history, which would imply that the large deformation was induced suddenly when the specimens were liquefied. On the other hand, the increment of $\gamma_{(DA)}$ of Toyoura sand turned out to be smaller when the specimen was subjected to the drained cyclic loading history.

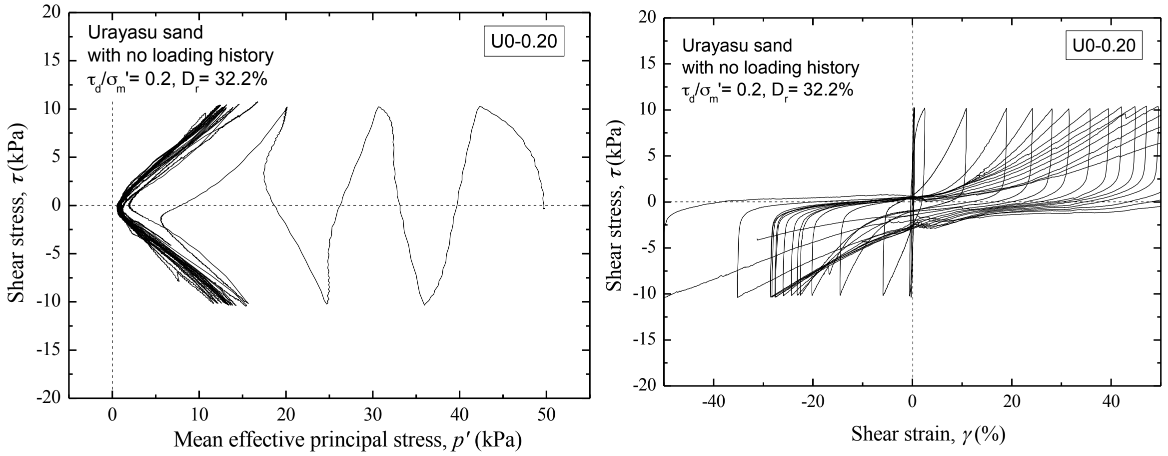

Figure 7 a) Effective stress path and b) stress-strain relation of Urayasu sand without drained vertical cyclic loading history

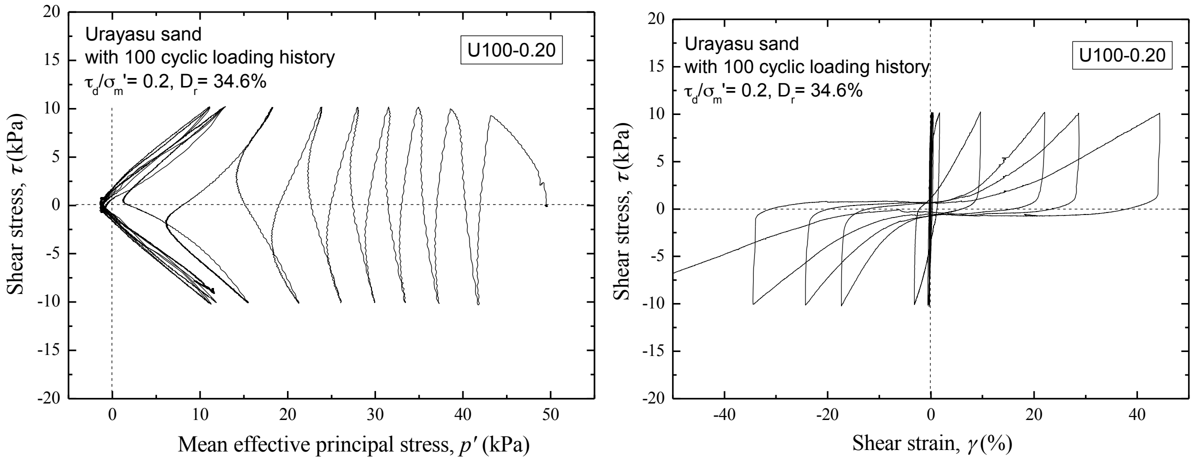

Figure 8 a) Effective stress path and b) stress-strain relation of Urayasu sand with 100 drained vertical cyclic loading history

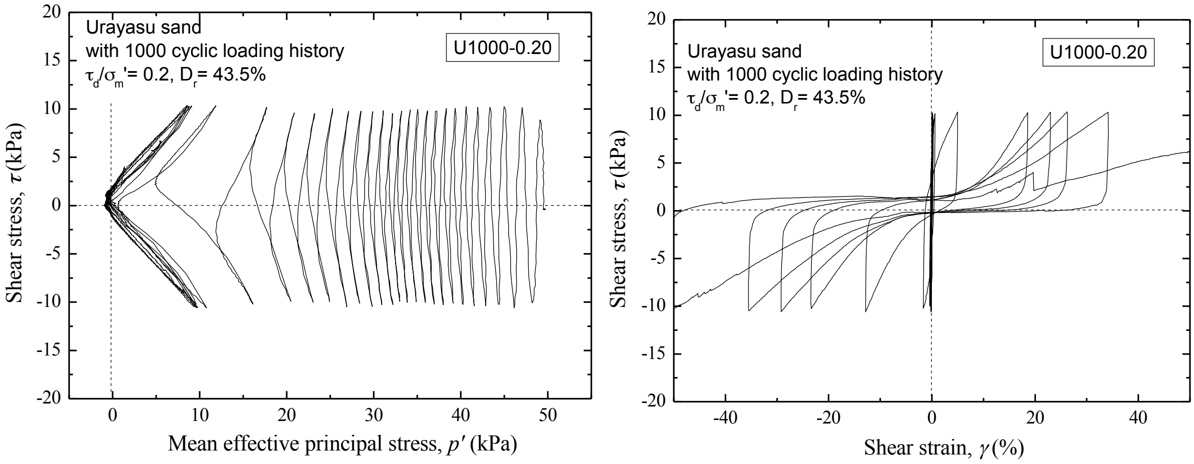

Figure 9 a) Effective stress path and b) stress-strain relation of Urayasu sand with 1000 drained vertical cyclic loading history

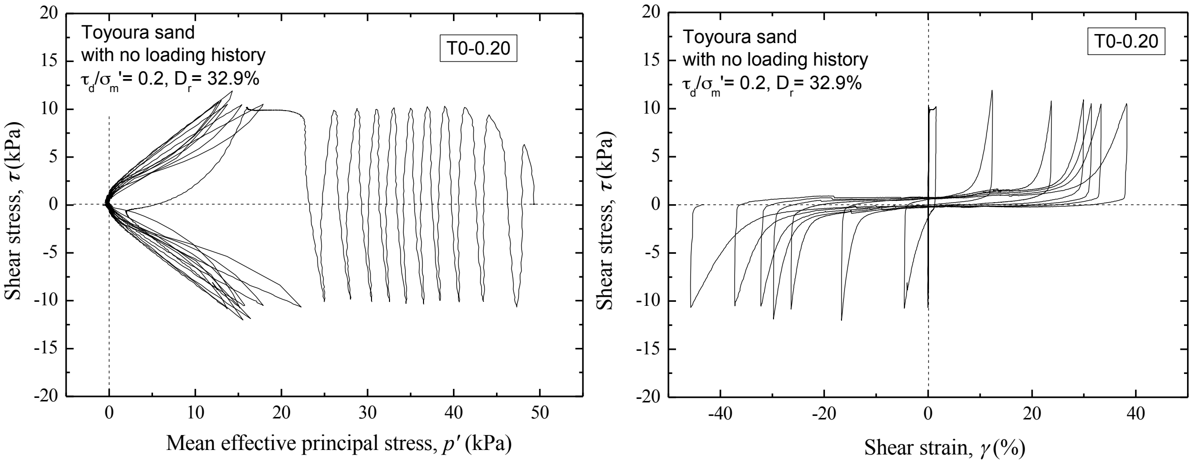

Figure 10 a) Effective stress path and b) stress-strain relation of Toyoura sand without drained vertical cyclic loading history

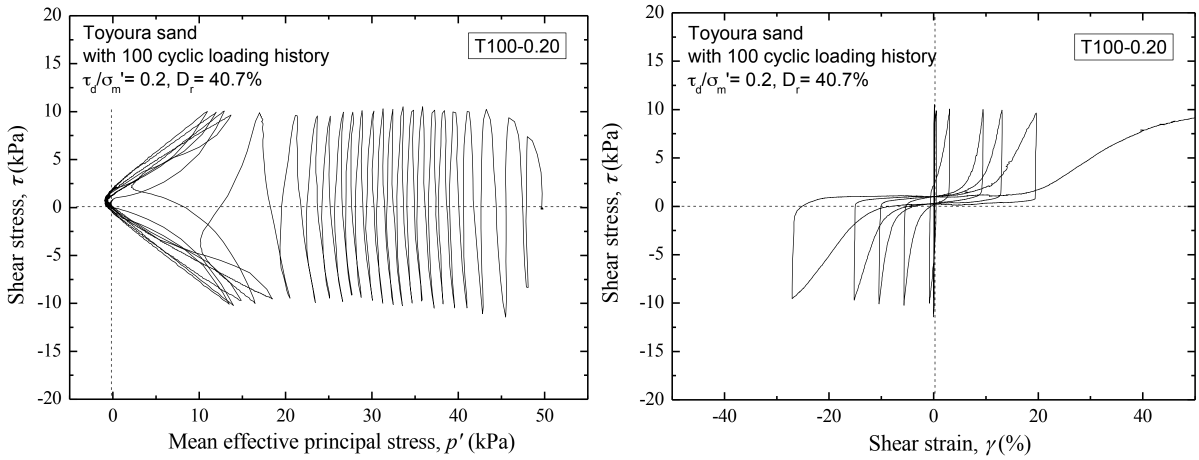

Figure 11 a) Effective stress path and b) stress-strain relation of Toyoura sand with 100 drained vertical cyclic loading history

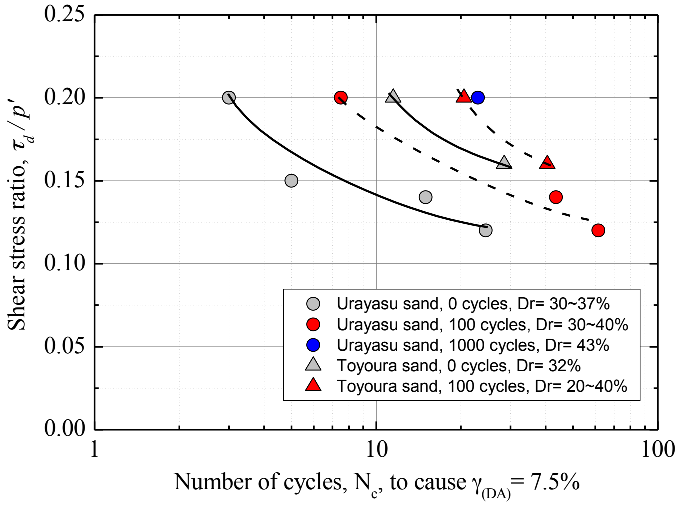

Figure 12 Shear stress ratios required to cause $\gamma_{(DA)}$ of 7.5%

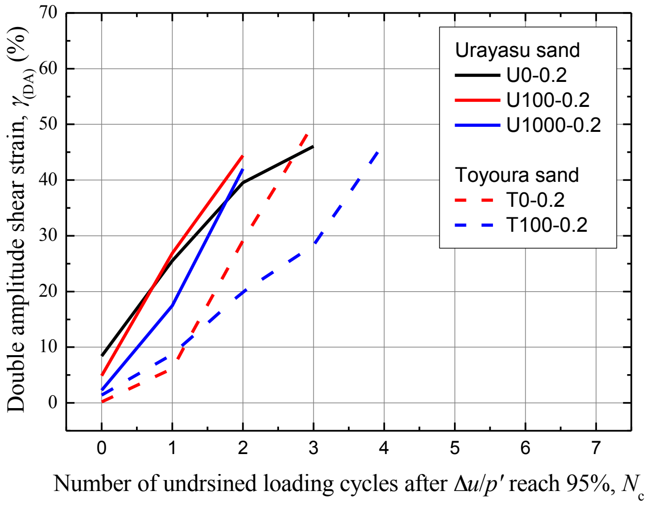

Figure 13 Relationship between N_c after liquefaction and $\gamma_{(DA)}$

Conclusion

In order to investigate the effect of drained vertical cyclic loading history on the small strain shear moduli and the liquefaction characteristics of boiled silty sand with Fc= 30% (Urayasu sand), a series of dynamic small strain measurement and undrained cyclic torsional shear tests was performed. The boiled silty sand used in this study was retrieved in Urayasu city where severe liquefaction occurred by the 2011 off the Pacific Coast of Tohoku earthquake. Toyoura sand which has no fines content was also used for comparison. The test results were summarized as follows;

1. The increases in small strain shear moduli due to applying drained vertical cyclic loading were observed in both Urayasu sand and Toyoura sand. 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.

2. The effect of vertical loading history on the liquefaction resistance was investigated. It was found that the liquefaction resistance of both Urayasu sand and Toyoura sand increase due to the increase in drained cyclic loading history. However, for Urayasu sand, such enhanced initial soil structure has little direct effect on the large strain characteristics, as compared with Toyoura sand.

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