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EFFECT OF CYCLIC SHEAR LOADING HISTORY ON LIQUEFACTION RESISTANCE OF IN-SITU SANDY SOILS IN LARGE STRAIN TORSIONAL SHEAR TESTS

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ABSTRACT

In order to investigate aging effects on liquefaction properties of in-situ sandy soils, a series of undrained cyclic torsional shear tests was performed on in-situ frozen and their reconstituted samples which were retrieved from Pleistocene deposits. The specimens were subjected to isotropic consolidation at a specified confining stress which is almost equivalent to the in-situ overburden stress at the depth of sampling. After isotropic consolidation, some of the reconstituted samples were subjected to 20,000 cycles of torsional shear load with double amplitude shear strain of 0.2% under drained condition in order to enhance the inter-locking between soil particles which would correspond to the aging effect. In addition, before the undrained cyclic torsional shear tests, initial small strain shear moduli of the specimens were measured by dynamic measurement. It was confirmed that the initial small strain shear moduli of the specimens were increased by applying drained cyclic torsional shear loading, and generally correspond to the liquefaction resistance of the specimens. However, during the undrained cyclic loading process, different tendency of change in the double amplitude shear strain could be observed between the in-situ frozen sample and its reconstituted sample which has drained cyclic loading history. These results may suggest that the development of shear strain due to liquefaction was affected by the types of aging effects, since the soil structure of in-situ frozen sample from the Pleistocene deposit would have both the inter-locking and the cementation effects while only the inter-locking effect was enhanced for the reconstituted sample.

Keywords: Liquefaction, torsional shear, aging effect, shear moduli, small strain

INTRODUCTION

The relative density and the particle gradation including a fines content of the soil deposit are important parameters to affect the liquefied soil behaviour. On the other hand, it is well known that liquefaction behaviour caused by earthquake motion is highly influenced by not only the above factors but also natural aging effects of the soil deposit.

Kiyota et al. (2009a) compared liquefaction resistance between a high quality undisturbed sample which was taken by in-situ frozen technique and its reconstituted sample. They reported that the liquefaction resistance of in-situ frozen sample which would contain natural aging effects was obviously larger than that of the reconstituted sample which would not have such effect. Hatanaka et al. (1988) and Goto et al. (1992) among others also reported such aging effect on the liquefaction properties through their relevant laboratory experiments.

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Yoshimi et al. (1994) pointed out that the liquefaction resistance is increased by applying drained cyclic loading before liquefaction test, since the inter-locking between the soil particles would be structured. The effect of cyclic loading history on the soil behaviour including liquefaction and change in small strain characteristics which reflect the current soil structure (Santamarina, 2001) has been discussed in previous studies.

Kiyota et al. (2009a) reported that the natural aging effects of sandy soils would consist of both the inter-locking and cementation effects between soil particles, and the aging effects as well as the liquefaction resistance would be estimated by the value of small strain characteristics of the soil. Tokimatsu and Hosaka, (1986) and Teachavorasinskun et al. (1994) among others also reported that the liquefaction resistance, which is affected by the aging effect due to natural or artificial procedure, has been correlated with small strain characteristics. On the other hand, Wichtmann and Triantafyllidis (2004) showed only moderate changes of small strain characteristics even though 100,000 cycles of vertical loading was applied on the specimen. Koseki et al. (2000) compared the small strain characteristics measured by static measurement during isotropic consolidation and liquefaction process with Toyoura sand. They summarized that the values of small strain moduli during liquefaction are smaller than those during isotropic consolidation because of damage to soil structure due to liquefaction.

As far as the authors know, there have been few studies that deal with the aging effects, liquefaction resistance and small strain characteristics by using a torsional shear apparatus, in particular with the in-situ samples including those retrieved by in-situ freezing sampling technique. In this study, in order to investigate the effect of cyclic loading history on such soil properties, a series of drained and undrained cyclic shear loading tests was performed with a medium size large strain torsional shear apparatus.

TEST APPARATUS AND MATERIALS

Details of the hollow cylindrical apparatus employed have been described in previous study (Kiyota et al., 2008), so that brief outlines will be shown here.

Figure 1 shows a torsional shear apparatus used in this study. The apparatus was modified to enlarge the effective range of torsional displacement. As a consequence of the modification, it was made possible to achieve 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.

The test materials were Edo-river B and Edo-river C sands, which were taken by in-situ freezing sampling technique from Pleistocene deposits (denoted as FSs). The reconstituted samples (denoted as RSs) that the dry densities were adjusted to the same levels as those of respective FSs were also prepared. After isotropic consolidation, some of the RSs were subjected to 20,000 cycles of torsional load with double amplitude shear strain, $\gamma_{(DA)}$, of 0.2% under drained condition. Tokimatsu and Hosaka (1986) among others adopted this procedure to enhance the stability of the soil structure due to inter-locking effect without significantly changing the specimen density, and the RSs which have such initial cyclic loading histories are called RSCLs. Kiyota et al. (2009a) conducted a series of undrained cyclic triaxial tests on some of the above samples, and confirmed that aging effects against liquefaction of FSs are stronger than those of RSs and RSCLs because the soil structure of FSs was enhanced by both inter-locking and cementation effects. Basic properties of tested samples are summarized in Table 1.

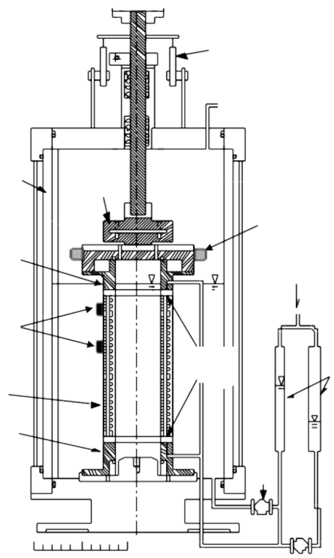


Figure 1. Torsional shear apparatus

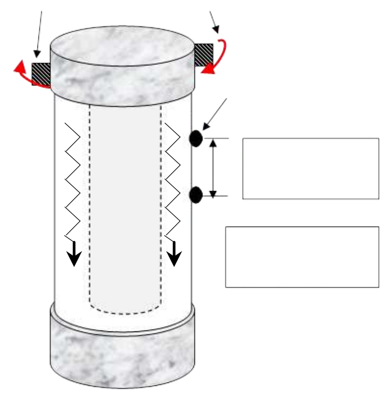


Figure 2. Diagram of S wave triggers and accelerometers on a hollow cylindrical specimen

Table 1. Basic properties of testes samples (after Kiyota et al., 2008)

Sample	Depth (GL- m)	σ_z'* (kPa)	D_{50} (mm)	F_c (%)	U_c	e_{max}	e_{min}	*Geological age*
Edo-river B	10.3~11.0	100	0.561	3.0	4.3	1.043	0.710	Young Pleistocene deposit ($130*10^3$ yr)
Edo-river C	17.0~ 17.6	160	0.153	9.4	1.8	1.765	1.052	Old Pleistocene deposit ($130*10^3$ ~ $300*10^3$ yr)

* σ_z' is in-situ overburden stress at the depth of sampling

After saturating the specimens, they were consolidated to an isotropic effective stress, σ'_m of 100 kPa for Edo-river B sand and 160 kPa for Edo-river C sand, which is almost equivalent to the in-situ overburden stress at the depth of sampling, with a back pressure of 200 kPa.

As small strain characteristics, the shear modulus, G_d, was dynamically measured for some specimens immediately before the undraied cyclic torsional shear tests. A pair of accelerometers was used to measure the arrival of *S* wave at two different heights on the side surface of the specimen as shown in Fig. 2. The *S* wave in a form of a single sinusoidal wave at a frequency of 2 kHz was generated by a pair of wave sources (triggers) attached on the top cap, which were excited simultaneously in the torsional direction. From the *S* wave velocity, V_s, as formulated in Fig. 2, the small strain shear moduli, G_d, were evaluated as $G_d = \rho V_s^2$, where ρ is mass density of the specimen.

After the above procedures, undrained cyclic torsional shear tests with constant amplitude of cyclic shear stress, τ_d/σ'_m, were performed. The measured shear stress, τ_d, was corrected for the effects of membrane force that was measured by using water-membrane specimen directly (Kiyota et al., 2008). Throughout the cyclic torsional loading, the vertical strain of the specimen was maintained to be zero, by using a mechanical locking device for the vertical displacement of the top cap.

TEST RESULTS

Small strain shear moduli before liquefaction

Small strain shear moduli, G_d, were measured by dynamic measurement before conducting undrained cyclic torsional shear tests. Figure 3 shows relationships between the G_d and relative density, D_r, of Edo-river B and C sands which were measured at effective isotropic confining pressure, σ'_m= 100 kPa and 160 kPa, respectively. It should be noted that the D_r values of RSs and RSCLs could not be adjusted exactly to those of FSs, especially for Edo-river B sand. However, the G_d values of RS and RSCLs of Edo-river B sand were lower than or equal to those of FSs in spite of the fact that the RSs had a higher D_r value by about 20% than the FSs.

In order to normalize for the effects of different void ratios, *e*, the following function proposed by Hardin and Richart (1963) is applied to normalize the small strain shear moduli, G_d.

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

The average values of $G_d/f(e)$ of all samples are shown in Fig. 4. The results of in-situ PS logging are also shown in the figure with thick horizontal lines. The range of the horizontal line represents the in-situ stress states (estimated assuming σ'_h/σ'_v= 0.5) of the soil layer where the FSs were retrieved. For the Edo-river B sand, since the $G_d/f(e)$ values of the FSs were similar to the results of in-situ PS logging, it could be inferred that the disturbance of the FSs was small. On the other hand, Edo-river C sand might have been more or less disturbed, since the $G_d/f(e)$ values of the FS were somewhat lower than the results of in-situ PS logging.

The ratios of average value of $G_d/f(e)$ of the RS to those of the FSs, $G_{d(RS)}/G_{d(FS)}$ are 0.61 and 0.77 for Edo-river B and C sands, respectively. Since it would be reasonable to assume that the FSs from Pleistocene deposits have their own aging effects while their RSs do not have such effects, the values of $G_{d(RS)}/G_{d(FS)}$ reflect probably the degree of aging effects of each deposit. Kiyota et al. (2009a and 2009b) reported that the aging effects are considered to be developed by inter-locking and cementation. In the case of Pleistocene deposits like the FSs of Edo-river B and C sands, the cementation effect may have taken place due to the diagenesis.

If the aging effects of specimen could be linked with the G_d value as reported by previous studies, they would be more or less produced by drained cyclic loading history. By comparing the results from RSs and RSCLs on Figs. 3 and 4, the increases in the G_d values due to applying 20,000 cyclic loading were recognized on both Edo-river B and C sands. Tokimatsu and Hosaka (1986) among others reported that such drained small cyclic loading caused increase in stiffness as well as liquefaction resistance of the specimen. The change in the liquefaction resistance is shown later.

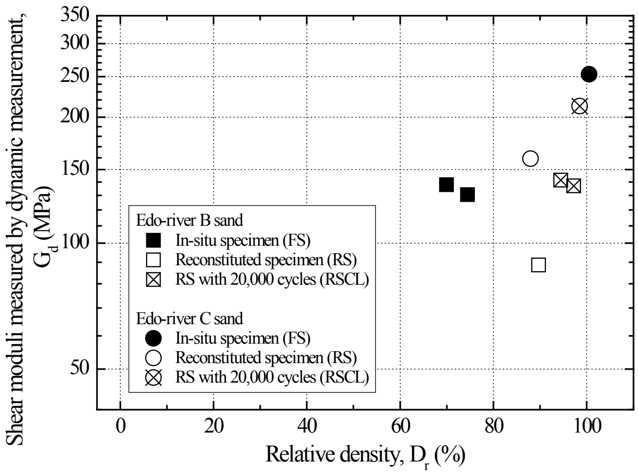


Figure 3. Relationship between relative density, D_r and small strain shear moduli, G_d

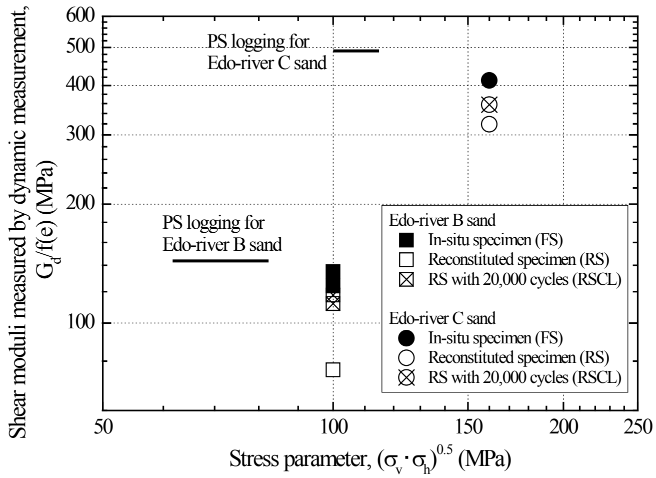


Figure 4. Relationship between stress parameter, $(\sigma_v \cdot \sigma_h)^{0.5}$ and normalized small strain shear moduli, $G_d/f(e)$

Liquefaction tests

A typical test result on the FS of Edo-river C sand is shown in Fig. 5. In the effective stress path, the cyclic mobility was observed where the effective stress was recovered repeatedly after showing almost zero effective stress state. The double amplitude shear strain, $\gamma_{(DA)}$, increased with increase in the number of cycles, N_c, and caused by undrained cyclic loading exceeded 100% at the end of the test.

The specimen deformation at several states as numbered 1 through 4 in Fig. 5 is shown in Photo 1. A set of small accelerometers attached on the side surface of the specimen can be seen in the photos. The strain localization was observed at strain levels of less than 10% as shown in Photo 1b). After the strain localization, the development of the shear band could be observed in the upper part of the specimen, and the specimen was finally twisted just under the top cap as shown in Photo 1c) and d). Although the shear strain of -60% was measured at state 4, it is no longer the actual shear strain of the whole specimen.

In all of these large strain liquefaction tests with Edo-river B and C sands, the $\gamma_{(DA)}$ values continued to increase and approached almost 100% that is the full capacity of the apparatus. However, non-uniform deformation or strain localization was observed only at lower shear strain levels as shown in Photo 1a). To separate the uniform deformation from the non-uniform deformation of the specimen, Kiyota et al. (2008) introduced a limiting value of double amplitude shear strain to cause strain localization, $\gamma_{L(DA)}$, based on the change in the deviator stress during undrained cyclic shear loading. However, this paper will not include details of the limiting value, $\gamma_{L(DA)}$. Refer to Kiyota et al. (2008, 2010) for the discussion about $\gamma_{L(DA)}$ and the results of the other specimens with which the testing conditions as well as the tested samples are different from those here.

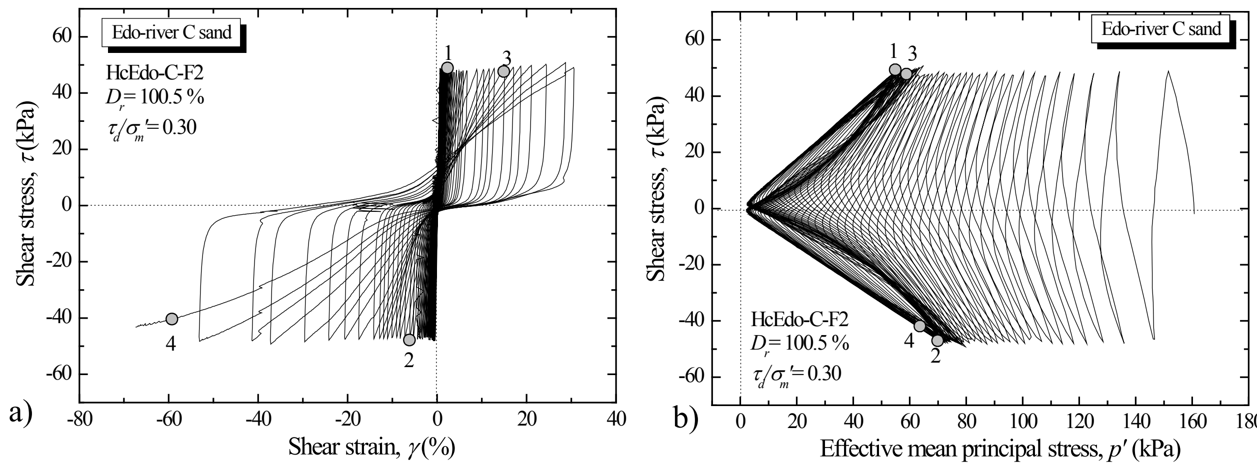
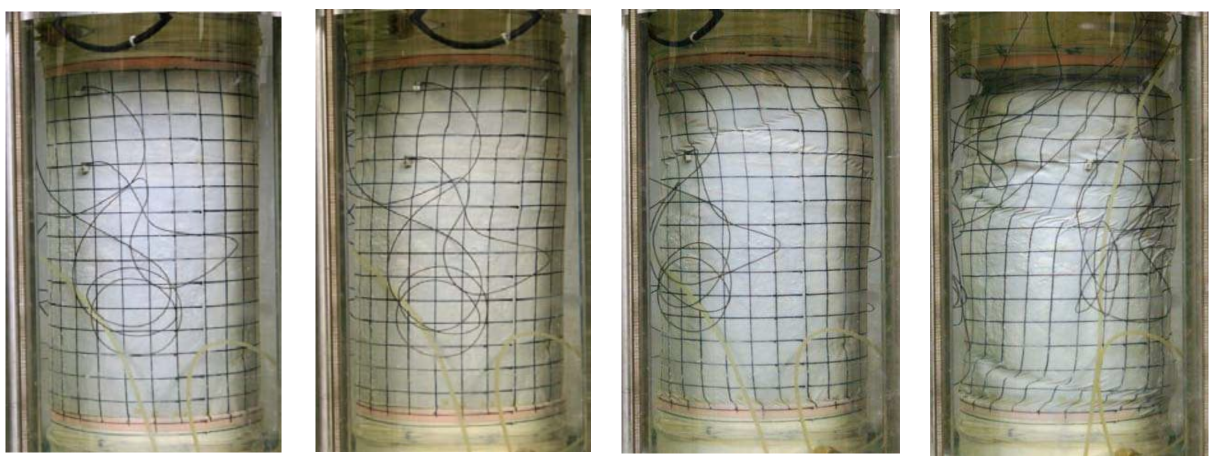


Figure 5. Typical test result (a) Stress strain relationship and b) Effective stress path) of FS of Edo-river C sand (D_r= 100.5%)



a) 1. γ= 3 % b) 2. γ= -7 % c) 3. γ= 15 % d) 4.γ= -60 %

Photo 1. Specimen deformation at status 1 through 4 in Fig. 5

Figures 6 and 7 show the relationship between cyclic shear stress ratio, τ_d/σ'_m, and number of cycles, N_c, required to cause double amplitude shear strain, $\gamma_{(DA)}$= 7.5% of Edo-river B and C sands. The $\gamma_{(DA)}$ value of 7.5% corresponds to the double amplitude vertical strain, $\varepsilon_{v(DA)}$, of 5% for the conventional undrained cyclic triaxial test. The liquefaction test results by triaxial apparatus (Kiyota et al., 2009a) were also plotted in order to complement the results in this study.

The liquefaction resistances defined as the τ_d/σ'_m to cause $\gamma_{(DA)}$= 7.5% in 20 cycles, RL_{20}, of these samples are also shown in Figs. 6 and 7 which seem to be larger in the order of the FS, RSCL and RS. Since the number of tests was limited and the test results were scattered significantly, it was difficult to identify the liquefaction curves for FS and RSCL of Edo-river B sand and RS of Edo-river C sand. Therefore, their liquefaction curves are highly complemented by the results from the triaxial tests.

The remarkable feature shown in Figs. 6 and 7 was the difference in the RL_{20} values between RSs and RSCLs. The values of RL_{20} of the RSCLs seem to be increased significantly and approached those of the FSs. Although this tendency has been recognized in the triaxial tests by many researchers, it was also confirmed by torsional test in this study.

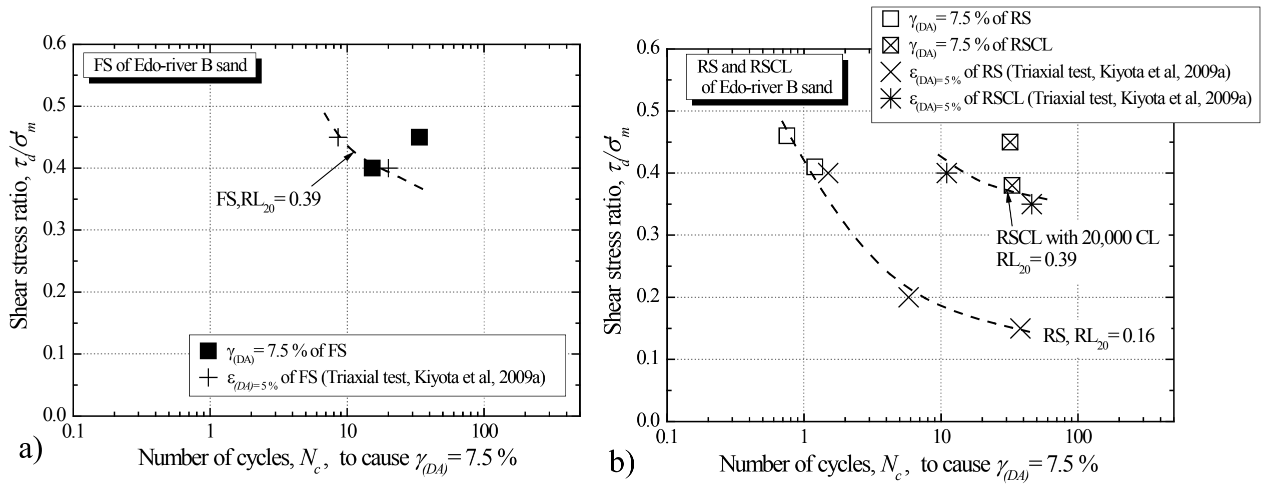


Figure 6 Shear stress ratios required to cause double amplitude shear strain of 7.5% for a) in-situ frozen sample and b) reconstituted samples for Edo-river B sand

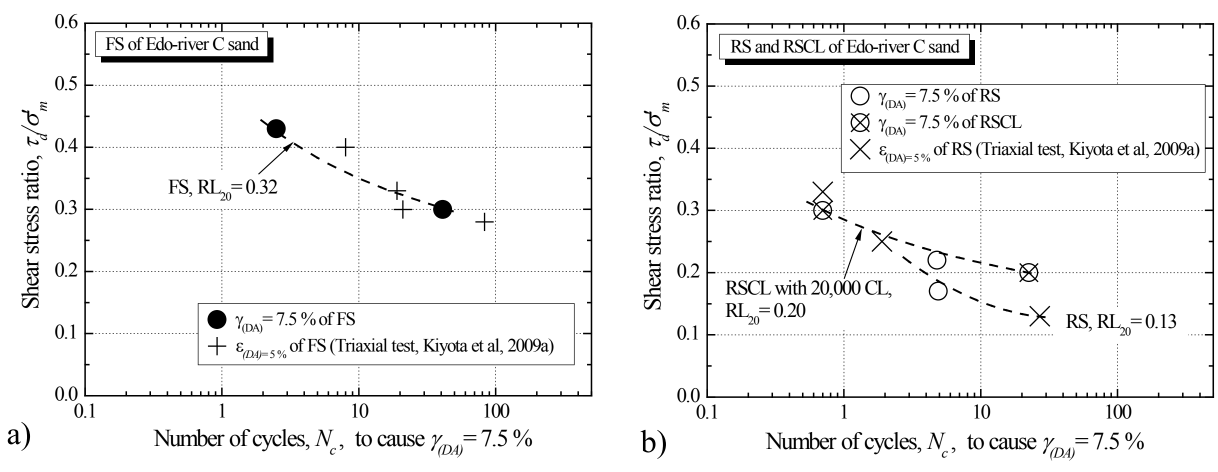


Figure 7 Shear stress ratios required to cause double amplitude shear strain of 7.5% for a) in-situ frozen sample and b) reconstituted samples for Edo-river C sand

DISCUSSIONS

Figure 8 shows the relationship between the RL_{20} and small strain shear moduli. The values in the figure represent the normalized small strain shear moduli measured immediately before undrained cyclic torsional shear test, G_{dN} of each specimen in MPa. Since the σ'_m for the Edo-river C sand was 160 kPa while that of the Edo-river B sand was 100 kPa, the small strain shear moduli of the Edo-river C sand were normalized for the effective confining pressure before liquefaction by the following equation.

$$G_{dN} = G_d \left(\frac{\sigma'_{m0}}{\sigma'_m} \right)^n \tag{2}$$

where σ'_{m0} is reference pressure (100 kPa in this study), the power number, n, was set to 0.5, which was shown by Tatsuoka and Kohata (1995) for fine sand.

As shown in Fig. 8, relationships between the values of G_{dN} were unique for each sample, while they were different from each other, depending on the types of the tested material. A larger value of RL_{20} was observed when G_{dN} was larger. In the case of the RSCL of Edo-river B sand with 20,000 cycles, almost the same values of G_{dN} and RL_{20} were obtained as those of the FS. In the case of Edo-river C sand, although the values of G_{dN} and RL_{20} of the RSCL could not reach those of the FS, they were significantly increased from the original values of the RS. In this study, therefore, the aging effects could be more or less produced by drained cyclic loading history, and small strain shear moduli by dynamic measurement, G_{dN}, was found to be relevant in estimating the liquefaction resistance, which is affected by the aging effects. Tokimatsu et al. (1986) also showed similar results by triaxial test. In USA, guidelines for evaluating liquefaction resistance using shear wave velocity measurement were prepared by Andrus et al. (2003) for U.S. Department of Commerce.

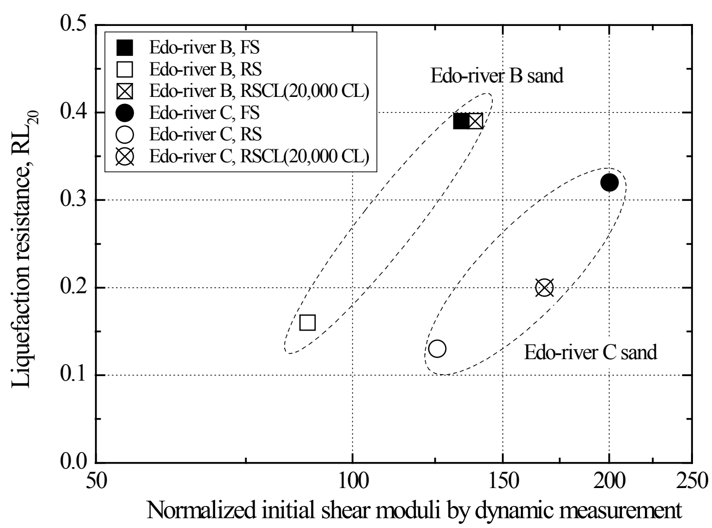


Figure 8 Relationship between small strain shear moduli, G_{dN} and liquefaction resistance, RL_{20} of tested samples

However, during the undrained cyclic loading process, different increase tendency of the double amplitude shear strain could be observed between the FS and RSCL. Figure 9 shows the relationship between the $\gamma_{(DA)}$ and number of cycles, N_c, for Edo-river B and C sands. The increase tendency of $\gamma_{(DA)}$ seems to depend on the value of τ_d/σ_m'. Figure 10 shows the relationship between the $\gamma_{(DA)}$ and the normalized number of cycles, $N_c/N_{c(60\%)}$, where $N_{c(60\%)}$ is defined as the number of cycles to cause $\gamma_{(DA)}$= 60%. Although the increment in the $\gamma_{(DA)}$ values of the RSCLs were small at an initial part of liquefaction, they were suddenly increased when the $N_c/N_{c(60\%)}$ were about 0.5 and 0.75 for Edo-river B and C sands, respectively. On the other hand, the increment in the $\gamma_{(DA)}$ values of FSs were rather gradual from the beginning to the end.

The above tendencies of Edo-river B and C sands from Pleistocene deposits suggest that it would be difficult to simulate the behavior of the FS which have a cementation effect by employing the RSCL even if the G_d values were adjusted by applying drained cyclic loading history.

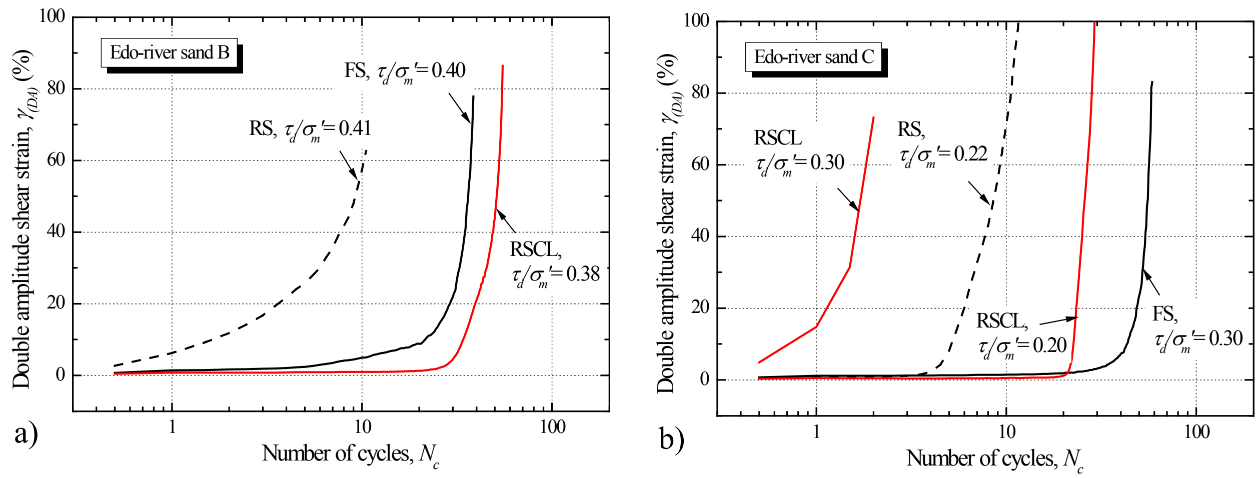


Figure 9 Relationship between number of cycles, N_c and double amplitude shear strain, $\gamma_{(DA)}$ during liquefaction test for a) Edo-river B sand and b) Edo-river C sand

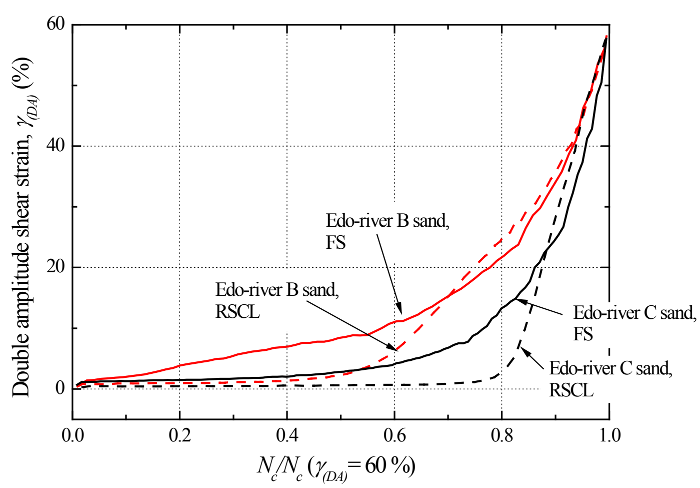


Figure 10 Relationship between normalized number of cycles, $N_c/N_{c(60\%)}$ and double amplitude shear strain, $\gamma_{(DA)}$ during liquefaction test for a) Edo-river B sand and b) Edo-river C sand

CONCLUSIONS

The present paper investigates the aging effects on both liquefaction properties and small strain characteristics of two kinds of in-situ frozen samples which were retrieved from Pleistocene deposit and their reconstituted samples with/without drained cyclic loading history. A series of undrained cyclic loading tests was performed in large strain torsional shear apparatus. The conclusion could be summarized as follows;

a) Higher values of small strain shear moduli were obtained with the in-situ frozen samples than with the reconstituted samples before liquefaction test. The small strain shear moduli of the reconstituted samples increased due to drained cyclic loading history, since the inter-locking between the soil particles would be structured.

b) With respect to each sample, larger liquefaction resistance was observed with an increase in the small strain shear moduli which were measured immediately before the liquefaction test.

c) During undrained cyclic shear loading, different increase tendency of the double amplitude shear strain could be observed between in-situ frozen sample and reconstituted sample that has initial drained cyclic loading history. It can be considered that the soil structure of in-situ frozen sample from the Pleistocene deposit would have both the inter-locking and the cementation effects while only the former effect was dominant for the reconstituted sample. Therefore, it would be difficult to simulate the behavior of in-situ frozen sample by employing the reconstituted sample even if the small strain shear moduli of the reconstituted sample were adjusted to those of the in-situ frozen sample.

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