EFFECTS OF SAMPLE DISTURBANCE ON SMALL STRAIN CHARACTERISTICS AND LIQUEFACTION PROPERTIES OF HOLOCENE AND PLEISTOCENE SANDY SOILS

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ABSTRACT

To investigate liquefaction properties of sandy soils, undrained cyclic loading tests are usually performed. However, it would be difficult to simulate fully the actual soil behaviour through the laboratory tests because the tested sample can be disturbed even though it is taken by in-situ freezing technique. In this study, by using three kinds of in-situ frozen sandy soils which were taken from Holocene and Pleistocene deposits and their reconstituted samples, their volume change properties were measured during freeze and thaw processes at different confining pressures of 30 kPa and 98 kPa. In order to investigate the effects of the possible sample disturbance on the liquefaction resistance, small strain characteristics were measured as well, which would reflect the soil structure. Decreases in the small strain characteristics and the liquefaction resistance were observed in case of the Holocene specimens that were thawed at the confining pressure that was lower than the in-situ overburden stress. On the other hand, in case of the Pleistocene specimens, the effects of the confining pressure during the thaw process on the small strain characteristics and the liquefaction resistance were small. Such contrastive feature between the Holocene and the Pleistocene samples could be linked with the difference in the types of their natural aging effects.

Key words: in-situ frozen sample, liquefaction, sample disturbance, sand, small strain characteristics (IGC: D6)

INTRODUCTION

A laboratory test on in-situ frozen samples is a well-known high quality method for understanding the actual behaviour of sandy soils. However, even the in-situ frozen sample is probably disturbed due to the possible expansion during ground freezing, and the disturbance would affect significantly the test results.

Yoshimi et al. (1978) and Goto (1993) reported the limiting values of the amount of fines, the level of confining stress and volumetric strain during freeze process for preventing disturbance of soil structure due to the freezing. The level of the confining stress during thaw process would also affect the test results because the soil structure would be changed due to the different stress histories. However, there are no practical proposals for the level of confining stress to be employed during the thaw process. In this connection, Yoshimi et al. (1984) reported that change in the liquefaction resistances was negligible even if the confining stresses during the thaw process were changed in the range of 5 kPa to 98 kPa.

Meanwhile, the small strain quasi-elastic stiffness is one of the important parameters that reflect the soil structure as well as the extent of specimen disturbance. Santamarina et al. (2001) suggested that the small-strain behaviour reflects the current fabric, while the large stress-strain behaviour is affected by fabric changes. Tokimatsu and Hosaka (1986) among others reported that the extent of specimen disturbance could be evaluated by comparing the small strain characteristics measured in the laboratory and in the field by PS logging.

Koseki et al. (1999) and Koseki and Ohta (2001) reported that both the liquefaction resistance and the small strain characteristics are influenced by the aging of the sample. The change in the liquefaction resistance due to sample disturbance, including the loss of the aging effect, which is caused by sampling, sample preparation and freeze-thaw process, has been also investigated (Tokimatsu et al., 1986; Goto, 1993; Yoshimi et al., 1984; Teachavorasinskun et al., 1994). However, the possible link between the sample disturbance and the aging of the sample is not fully understood.

In this study, to investigate the effect of confining pressure during the thaw process on the sample disturbance, three different in-situ frozen sandy soils which were taken from Holocene and Pleistocene deposits, were thawed at...
Table 1. Basic properties of tested samples

<table>
<thead>
<tr>
<th>Sample</th>
<th>Depth (GL-m)</th>
<th>Dₜ (mm)</th>
<th>Fᵢ (%)</th>
<th>Uᵢ</th>
<th>εₑₘₐₓ</th>
<th>εₑᵣₘ</th>
<th>Vₛ⁺ (m/s)</th>
<th>Geological age</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tone-river</td>
<td>11.8 – 12.1</td>
<td>0.188</td>
<td>1.2</td>
<td>2.0</td>
<td>1.066</td>
<td>0.675</td>
<td>240</td>
<td>Holocene deposit (8,000 yr)</td>
</tr>
<tr>
<td>Edo-river B</td>
<td>10.3 – 11.0</td>
<td>0.561</td>
<td>3.0</td>
<td>4.3</td>
<td>1.043</td>
<td>0.710</td>
<td>270</td>
<td>Young Pleistocene deposit (130*10³ yr)</td>
</tr>
<tr>
<td>Edo-river C</td>
<td>16.0 – 16.3</td>
<td>0.189</td>
<td>2.9</td>
<td>2.1</td>
<td>1.132</td>
<td>0.714</td>
<td>390</td>
<td>Old Pleistocene deposit (130<em>10³ – 300</em>10³ yr)</td>
</tr>
</tbody>
</table>

*: Vₛ measured by in-situ PS logging

Fig. 1. Schematic cross section of soil profile where in-situ frozen samples are retrieved (Original diagram by Endo et al. (1983), Kiyota et al. (2008))

TESTED MATERIALS

Three kinds of in-situ frozen samples (denoted as FSs) were tested in this study and were taken from a Holocene deposit (denoted as Tone-river sand) and Pleistocene deposits (denoted as Edo-river B and C sands). They are sandy soils, and their fines contents are less than three percent as summarized in Table 1. Figure 1 shows the schematic cross section of soil profile where the FSs of the Pleistocene deposits were retrieved. The geological age of the Edo-river B sand is younger than that of the Edo-river C sand because the former sample was taken from Pleistocene terrace deposit which covers the latter one. Although the Tone-river sand was taken at a location that is different from the Edo-river B and C sands, it corresponds geologically to the Holocene deposit shown in

TEST APPARATUS

An automated triaxial apparatus as illustrated in Fig. 2 was used for this study. The cylindrical specimen used was approximately 50 mm in diameter and 100 mm in height. A deviator load was measured with a load cell fixed between the loading piston and the specimen top cap in the cell. A volume change of the saturated specimen during isotropic consolidation was obtained from the amount of pore water expelled from or sucked into the specimen by measuring the water height in a burette that was connected to the specimen with a low-capacity differential pressure transducer.

The vertical strain of the specimen was measured with two types of transducers; a normal external transducer for large strain, and a pair of local deformation transducers (LDTs) (Goto et al., 1991) for small strain. The vertical static Young’s modulus, $E_v$, was evaluated from the small cyclic stress-strain relationships obtained by us-
Fig. 3. Diagram of S wave triggers and accelerometers on a specimen

Fig. 4. Definition of wave travel time

Fig. 5. Schematic drawing of test apparatus during freeze and thaw processes

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Fig. 3. Diagram of S wave triggers and accelerometers on a specimen

Fig. 4. Definition of wave travel time

were cored out of the frozen samples having an original diameter of 15 cm by a core cutter machine in the freezer. In the case of the Tone-river sand and the Edo-river B sand, although the cylindrical specimen with a diameter of 5 cm were also cored out of the frozen samples, the operation was carried out with pouring a calcium chloride solution at a temperature of $-12^\circ\text{C}$ on the specimens under an atmospheric temperature of about $20^\circ\text{C}$. The specimens were transported to the freezer again immediately after the coring.

The FSs were set into the triaxial cell that was brought in the freezer, and a confining pressure was applied. In this study, different confining pressures of 30 kPa and 98 kPa were applied by reducing the back pressure using a vacuum pump, and the initial dimension of the specimen before thawing was measured in the freezer. Incidentally, the confining pressure of 98 kPa is almost equivalent to the in-situ overburden stress at the depth of sampling of the Tone-river sand and the Edo-river B sand as well as the limit value of the capacity of conventional vacuum pumps.

After the specimen preparation, the triaxial cell was transported back to the testing room. The FSs were thawed under an atmospheric temperature of about $25^\circ\text{C}$ while keeping the confining pressure of 30 kPa or 98 kPa. In this study, deformation of the FSs was measured during the thaw process. Seven gap sensors (proximity transducers) shown in Fig. 5 were used to measure vertical and horizontal deformations of the specimen during the thaw process. To measure the horizontal deformation of the specimen, an aluminium sheet was employed as the target of the gap sensors. The temperature of the surface of the specimen during the thaw process was measured by an infrared temperature transducer. It should be noted that the deformation of the specimen during the initial stage of the thaw process could not be measured because it required approximately 15 minutes to transport the apparatus with the specimen from the freezer to the testing room.
After the thaw process, the FSs were saturated while keeping the respective confining pressure, 30 kPa or 98 kPa. They were then subjected to isotropic consolidation at a specified confining stress (100 kPa for Tone-river sand and Edo-river B sand; and 160 kPa for Edo-river C sand) which is equivalent to the in-situ overburden stress at the depth of sampling. The small strain moduli by static and dynamic measurements were measured at several stress states during the isotropic consolidation.

After the isotropic consolidation, undrained cyclic triaxial tests were performed with constant amplitude of cyclic deviator stress, which are called liquefaction tests here. In addition, after the saturation, some of the FSs which were thawed at 98 kPa were unloaded isotropically to zero confining stress, and unconfined compression tests were performed.

**Preparation of Reconstituted Specimens**

Reconstituted samples (denoted as RSs) were prepared by pluviating oven-dried particles through air at almost the same dry density levels as the FSs and saturated at a confining pressure of 30 kPa. Then, they were consolidated to the same isotropic effective stress levels as mentioned above on FSs with measuring the static and dynamic small strain characteristics.

After the isotropic consolidation, some of the RSs of Tone-river sand were subjected to 10,000 and 20,000 cycles of vertical load with double amplitude vertical strain, \( \varepsilon_{v(DA)} \) of 0.1% under drained condition. Tokimatsu and Hosaka (1986) among others adopted this procedure to enhance the stability of the soil structure without significantly changing the specimen density, and the RSs which have such initial cyclic loading histories are called RSCLs in this paper. The number of cycles and the amount of \( \varepsilon_{v(DA)} \) during the above initial cyclic loading should affect both the small strain characteristics with strain level of less than \( 10^{-3} \) and the liquefaction characteristics of the RSCL.

With regard to the number of cycles, for instance, the vertical stress subjected to the in-situ deposit could be changed largely at least once a year due to seasonal change in the water table. Moreover, from the report of Central Disaster Management Council, Japan (2006), large earthquake that is the same magnitude as the 1923 Kanto Earthquake could occur in 200–400 year period in the Kanto area where the FSs were retrieved, and the earthquake events may be equivalent to the initial cyclic loading applied in this study. Considering the above situation, since the geological age of the Tone-river Holocene sand is expected to be 8,000 years (see Table 1), the initial cyclic loading with 10,000 to 20,000 cycles may be of the same order as the change in the environment of in-situ deposit.

Since Kiyota et al. (2009) reported that the dynamic shear moduli, \( G_s(\text{thaw}) \), of the RSCL with 10,000 cycles of Tone-river sand approached those measured by in-situ PS logging, the RSCLs can be considered as the samples reproduced at the in-situ condition with respect to the small strain characteristics. However, because the purpose of the initial cyclic loading in the present study is to reproduce the possible aging effect on the RSs, the effects of the number of cycles and the amount of \( \varepsilon_{v(DA)} \) will not be focused hereafter.

Some of the RSCLs of the Tone-river sand were frozen at a confining stress of 98 kPa, followed by thawing at different confining pressures of 30 kPa and 98 kPa under drained condition. The vertical and horizontal strains during the freeze and thaw processes were measured in the same manner as mentioned above on the FSs during the thaw process. In order to freeze the RSCLs of the Tone-river sand, the pedestal of the triaxial apparatus was connected to the chiller that contains a circulation pump and a coolant bath with a coolant temperature controller as shown in Fig. 5. The triaxial cell with the specimen was placed in a temperature controlled box in which the temperature is kept at approximately 1°C. However, it was difficult to freeze fully the specimen with this system because the temperature of the whole specimen did not fall below 0°C. Therefore, the triaxial cell and the specimen were transported from the testing room to the freezer after the initial deformation of the specimen by freezing was stabilized in the temperature controlled box. The dimensions of the specimen after the full freezing were measured manually in the freezer. The thawing procedure of these frozen RSCLs was the same as that of FSs. After these procedures, liquefaction tests were performed on the RSs and the RSCLs.

In addition, one of the RSCLs of Edo-river C sand was also subjected to 20,000 drained cyclic loading with \( \varepsilon_{v(DA)} = 0.1\% \) after isotropic consolidation. Then it was unloaded isotropically from 160 kPa to zero confining stress, and attempts were made to perform the unconfined compression test.

**TEST RESULTS**

**Volume Change of In-situ Frozen Samples during Thaw Process**

Three kinds of FSs were thawed at different confining pressures, \( \sigma_{(thaw)} \), of 30 kPa and 98 kPa. Figures 6(a) and (b) shows typical time histories of vertical strain, \( \varepsilon_v \), and horizontal strains, \( \varepsilon_h \), which were measured at top, middle and bottom of the specimen with the FSs of Tone-river sand during thaw process at \( \sigma_{(thaw)} \) of 30 kPa, and the surface temperature of the specimen respectively. Figure 7 shows those during thaw process at \( \sigma_{(thaw)} \) of 98 kPa. Note again that since the initial part of the deformation could not be measured as mentioned above after setting the initial values at the beginning of the thaw process, continuous measurement of the values of \( \varepsilon_v \) and \( \varepsilon_h \) started in about 15 minutes in Figs. 6(a) and 7(a). A large initial strain rate caused by thawing under normal temperature could be inferred. The values of \( \varepsilon_v \) and \( \varepsilon_h \) at the beginning of the measurement (for about 15 min.) were about 90% or almost equivalent to those at the end of the measurement. The specimen deformation and temperature change during the thaw process were terminated in approximately six hours after the start of thawing. The \( \varepsilon_v \)
and $e_h$ measured manually after thaw process, $e_{v(thaw)}$ and $e_{h(thaw)}$, are also shown in the figures. The volumetric strains during the thaw process, $e_{vol(thaw)} = e_{v(thaw)} + 2e_{h(thaw)}$, were about 1.5% and 2.5% for $\sigma_{(thaw)}$ of 30 kPa and 98 kPa, respectively. The values of $e_h$ which were measured at top, middle and bottom of the specimen, exhibited peak states in approximately one hour after the start of thawing, and they decreased after the peak state. Such a decrease in the $e_h$ values can be explained qualitatively by volume change characteristic of the pore water, i.e., the specific gravity of the water changes with temperature, showing the maximum value at 4°C. Quantitatively, however, the $e_h$ values at the top, middle and bottom of the specimen were irrelevant to each other, while those measured at the bottom of the specimen were always the largest.

On the other hand, although the value of $e_v$ reached its maximum in approximately one hour after the start of thawing, it became almost constant thereafter, not exhibiting a clear peak state. The difference between the behaviour of $e_v$ and $e_h$ during thaw process can be explained by the different conditions of the top and side surfaces of the specimen. Basically, the frozen specimen thaws from its surface exposed to the room temperature, and the rate of thawing depends on the thermal diffusivity of the specimen. However, in this study, the side surface of the specimen was covered by the membrane having a thickness of 0.3 mm while the top surface was capped by the porous-stone and the duralumin cap having thickness of 5 mm and 50 mm, respectively. Such a different thermal transmitting condition of the specimen surfaces could cause different behaviour between the $e_v$ and $e_h$ during thaw process.

Figures 8 and 9 show typical time histories of $e_v$ and $e_h$ of the FSs of Edo-river B and C sands during the thaw process. The changes in the $e_v$ and $e_h$ values were terminated in less than six hours after the start of thawing for both samples. The $e_{vol(thaw)}$ values of Edo-river B sand were about 1.1% and 1.8% for $\sigma_{(thaw)}$ of 30 kPa and 98 kPa, respectively, while those of Edo-river C sand were somewhat smaller ($e_{vol}=0.7\%$ and $1.8\%$ for $\sigma_{(thaw)}$ of 30 kPa and 98 kPa, respectively). As was also the case with Tone-river sand, the values of $e_h$ exhibited peak states in approximately one hour after the start of thawing.

Figure 10 shows the relationships between the $e_{vol(thaw)}$ and the $\sigma_{(thaw)}$ during thaw process of the FSs. As indicat-
ed in the figure, difference in the average values of $\varepsilon_{\text{vol(thaw)}}$ at $\sigma_{\text{thaw}} = 98$ kPa was small among the three samples (2.2%, 2.1% and 1.9% for Tone-river, Edo-river B and C sands, respectively). On the other hand, the average value of $\varepsilon_{\text{vol(thaw)}}$ at $\sigma_{\text{thaw}} = 30$ kPa of Edo-river C sand was 0.6%, which was somewhat smaller than those of other samples (1.6% and 1.2% for Tone-river and Edo-river B sands, respectively). A possible reason for this is the difference in in-situ overburden pressures between Edo-river C sand and other samples. The in-situ overburden pressure of Edo-river C sand was about 160 kPa that is higher than the other samples (about 100 kPa). Since the possible volume expansion of Edo-river C sand during the in-situ freezing process would have been smaller than those of the others, it exhibited the smaller value of $\varepsilon_{\text{vol(thaw)}}$.

The volume changes of the FSs during isotropic consolidation, $\Delta \varepsilon_{\text{vol}}$, following the thaw process are also indicated by vertical arrows in Fig. 10. Although a larger $\varepsilon_{\text{vol(thaw)}}$ value was observed at larger $\sigma_{\text{thaw}}$, the differences in the residual volumetric strain ($\varepsilon_{\text{vol(thaw)}} + \Delta \varepsilon_{\text{vol}}$) after isotropic consolidation (IC) to 100 kPa (Tone-river sand and Edo-river B sand) and 160 kPa (Edo-river C sand) were small, except for one extremely large value shown in Fig. 10(c).

**Volume Change of Reconstituted Samples during Freeze and Thaw Processes**

The RSCLs with 10,000 cycles of Tone-river sand were frozen at a confining pressure of 98 kPa. Figure 11 shows a typical time history of the vertical and the horizontal strains, $\varepsilon_v$, $\varepsilon_h$, and the temperature of the surface of the specimen during the freeze process. The specimen deformation during the freeze process was terminated in approximately ten hours after the start of freezing in the temperature controlled box at the temperature of 1°C. The $\varepsilon_h$ value that was measured at the top of the specimen exhibited a peak state in approximately one hour after the start of freezing, and the temperature of the specimen was approximately 4°C at this peak state of $\varepsilon_h$. This tendency can be explained by the volume change characteristics of the pour water, as seen in the behaviour of the FSs during the thaw process. The volumetric strain, $\varepsilon_{\text{vol(freeze)}} = \varepsilon_{\text{v(freeze)}} + 2\varepsilon_{\text{h(freeze)}}$, was $-0.58\%$ at the end of the measurement. Note again that the $\varepsilon_{\text{vol(freeze)}}$ was measured manually after the specimen was frozen fully in the freezer at the
temperature of $-20^\circ$C. Therefore, the value of $\varepsilon_{\text{vol(freeze)}}$ shown in the figure is much larger than that obtained from the measured values of $\varepsilon_v$ and $\varepsilon_h$ during freezing in the temperature controlled box.

After the freeze process, the RSCLs with 10,000 cycles of Tone-river sand were thawed at different confining pressures of 30 kPa and 98 kPa. Figure 12 shows a typical time history of $\varepsilon_v$ and $\varepsilon_h$, and the temperature of the surface of the specimen during the thaw process. The value of $\varepsilon_{\text{vol(thaw)}}$ of the RSCL did not correspond with those of the FSs as shown in Fig. 7, due possibly to the effects of freezing rates that were different between the FSs and the RSCL. On the other hand, Yoshimi and Goto (1996) reported that $\varepsilon_{\text{vol(thaw)}}$ and $\varepsilon_{\text{vol(freeze)}}$ of in-situ frozen samples would be similar to each other if the volume change by freezing is insignificant. In this study, both $\varepsilon_{\text{vol(thaw)}}$ and $\varepsilon_{\text{vol(freeze)}}$ of the RSCL with 10,000 cycles of Tone-river sand were also similar to each other as shown in Figs. 11 and 12.

Figure 13 shows that the deformation of another RSCL with 10,000 cycles of Tone-river sand which was frozen and thawed at 98 kPa and 30 kPa respectively. Although the values of $\varepsilon_v$ and $\varepsilon_h$ during freeze process fluctuated, the value of $\varepsilon_{\text{vol(freeze)}}$ shown in Fig. 13(a) was of the same order as that shown in Fig. 11(a) because they had the same stress history and the same freezing confining pressure as each other. On the other hand, the value of $\varepsilon_{\text{vol(thaw)}}$ of RSCL thawed at 30 kPa as shown in Fig. 13(b) was smaller than that resulting from the confining pressure of 98 kPa shown in Fig. 12(a). This feature is consistent with that of FSs shown in Fig. 10.

**Liquefaction Test**

Figures 14 and 15 show the typical results of undrained cyclic triaxial test on FSs of Tone-river sand which were thawed at 30 kPa and 98 kPa, respectively. As indicated on the stress-paths shown in Figs. 14(a) and 15(a), the liquefaction processes of both samples were somewhat different from each other in spite of the same cyclic stress ratios applied, $\sigma_d/2\sigma_c' = 0.4$ where $\sigma_d$ and $\sigma_c'$ denote single amplitude of the cyclic vertical stress and the effective confining pressure at the end of isotropic consolidation, respectively. The effective stress of the FS which was thawed at 30 kPa was decreased more rapidly than that thawed at 98 kPa. In addition, as indicated on the stress-strain relations shown in Figs. 14(b) and 15(b), development of the vertical strain, $\varepsilon_v$, which shifted to the extension side could be observed with both samples.

Other series of undrained cyclic triaxial tests were performed with Edo-river B and C sands. Figures 16 and 17 show the typical results of undrained cyclic triaxial test on FSs of Edo-river C sand which were thawed at 30 kPa and 98 kPa, respectively. The effects of different confining pressures during the thaw process on the stress-paths were insignificant as compared with those for Tone-river sand. In the case of Edo-river B sand, similar test results to Edo-river C sand could be observed.

Figure 18 shows the relationships between the cyclic shear stress ratio, $\sigma_d/2\sigma_c'$, and the number of cycles, $N_c$, required to cause $\varepsilon_v(\text{DA})=3\%$ for the three kinds of samples. Note that the relative densities, $D_r$, shown in the figure were measured before the liquefaction tests. So far the author’s research group conducted another series of liquefaction tests by using the FSs of Tone-river sand and Edo-river B sand which were retrieved from the same bore-hole and at the same sampling depth as those used in the present study. These previous results by Urano (1998) and Mochizuki (2001) with the FSs thawed at $\sigma_c'(\text{thaw})=30$ kPa under normal temperature are also shown in the figure. For all the samples, the liquefaction resistance of the FSs was much larger than that of the RSs even if their $D_r$ values were similar to each other. These results are
Fig. 11. a) Vertical and horizontal strains of reconstituted specimen (RSCL) with 10,000 cyclic loading history (Tone-river sand) during freeze process at confining pressure of 98 kPa and b) surface temperature of specimen

Fig. 12. a) Vertical and horizontal strains of reconstituted specimen (RSCL) with 10,000 cyclic loading history (Tone-river sand) during thaw process at confining pressure of 98 kPa and b) surface temperature of specimen

Fig. 13. Vertical and horizontal strains of reconstituted specimen (RSCL) with 10,000 cyclic loading history (Tone-river sand), a) during freeze process at confining pressure of 98 kPa and b) during thaw process at confining pressure of 30 kPa

similar to those that have been reported by previous studies (e.g., Hatanaka et al., 1985). They suggest that the FSs would have a natural aging effect by which the soil structure is strengthened, while the RSs would not have such an effect.

It should be noted that, as shown in Fig. 18, the liquefaction resistances of the FSs which were thawed at 30 kPa were somewhat smaller than those of the FSs which were thawed at 98 kPa. In particular, in the case of the FS of Tone-river sand, the influence of the confining pres-
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Fig. 14. a) Effective stress path and b) stress-strain relation during liquefaction test of Tone-river sand (FS thawed at 30 kPa)

Fig. 15. a) Effective stress path and b) stress-strain relation during liquefaction test of Tone-river sand (FS thawed at 98 kPa)

Fig. 16. a) Effective stress path and b) stress-strain relation during liquefaction test of Edo-river C sand (FS thawed at 30 kPa)

sure during the thaw process on the liquefaction resistance seems to be larger than those of Edo-river B and C sands.

Figure 19 compares the liquefaction resistance curves between the RSCLs with/without the freeze and thaw history and the RSs of Tone-river sand. Larger liquefaction resistance could be obtained with the RSCLs than that of the RSs. In addition although there is only
one data for the RSCL with 20,000 cycles, it exhibited larger liquefaction resistance than the RSCL with 10,000 cycles. A possible reason for this feature is that the soil structure (or the inter-locking between soil particles) of the RSCLs was stabilized by the drained cyclic loading before the liquefaction test, and the increment in the stability depended on the number of initial cyclic loading.

Regarding the possible effects of the freeze and thaw history on the RSCLs with 10,000 cycles, the liquefaction resistances were almost the same between the RSCLs which were frozen and thawed at 98 kPa and those without the freeze and thaw history. On the other hand, the liquefaction resistance of the RSCLs which were thawed at 30 kPa was smaller than those of the above RSCLs. However, it should be noted that the difference between the average $D_r$ values of the specimens thawed at 98 kPa and 30 kPa was as large as 11.7%. To investigate the possible effect of the different $D_r$ values on the liquefaction resistance, the relationship between $D_r$ and the number of cycles, $N_c$, which were required to cause $e^{(DA)}_{s} = 3\%$ at $\sigma_3/2\sigma' = 0.4$ are shown in Fig. 20. The results of the RSCL with 20,000 cycles and the RSs exhibit an extremely large or small $N_c$ values, which could not be explained by the difference in their $D_r$ values. On the other hand, the dependency of $N_c$ on the $D_r$ values of the RSCLs with 10,000 cycles which were frozen and thawed at 98 kPa and those without the freeze and thaw history were consistent with each other as indicated by the broken-line in Fig. 20, while the $N_c$ value of RSCL which was thawed at 30 kPa was significantly lower than the corresponding value that could be inferred from the broken-line.

These test results suggest that the FSs and the RSCLs can be disturbed by a low confining pressure during thaw process, and the degree of disturbance depends on the type of soil. In addition, the FSs and the RSCLs of Tone-river sand were disturbed more easily than the FSs of Edo-river B and C sands. Possible reason for such a difference is that the Pleistocene samples (i.e., Edo-river B and C sands) would have both an inter-locking effect and a cementation effect between soil particles, while the Holocene sample (i.e., Tone-river sand) would have only the former effect.

**Unconfined Compression Test**

Barton (1993) showed that there are two main sources of aging effects, which include cohesion that is produced by the diagenetic alteration of sands as inter-locking and bonding (cementation) of particles. However, it is very difficult to show whether a sample has a cementation or not, because there are few methods to measure the cementation quantitatively. In addition, the cementation of Quaternary deposits is usually weak and thus not easy to measure. In this study, in order to investigate the cementation effects of the FSs and the RSCLs, unconfined compression tests on saturated specimens were performed. Tohno (1975) also showed that such cementation of the Quaternary sands can be evaluated by their unconfined compression strengths.

Figure 21 shows results of the unconfined compression tests on the FSs of Edo-river B and C sands. Theoretically, saturated cohesionless sands should have no unconfined compression strength. However, as shown in Fig. 21, the deviator stress exhibited a peak value (denoted as $q_u$) with the FSs of Edo-river B and C sands. In addition, the $q_u$ value of Edo-river C sand was larger than that of the Edo-river B sand.

These results suggest that the cementation was developed between soil particles of these Pleistocene sands, and the cementation of Edo-river C sand could be stronger than that of Edo-river B sand. This feature is reasonable when considering the geological age and the structure of both soil layers as shown in Fig. 1. On the other hand, the FS of Tone-river sand and the RSCL with 20,000 cycles of Edo-river C sand liquefied when the effective confining stress decreased to zero. The fact that the unconfined compression test could not be carried out with the FS of Tone-river sand, indicates that its larger liquefaction resistance shown in Fig. 17(a) in comparison with that of the RS is due not to cementation effects but due to an inter-locking of soil particles. In addition, from the test results of the RSCL of Edo-river C sand, it can be
inferred that the cementation effect could not be reproduced even if 20,000 drained cyclic loading with $\varepsilon_{(DA)}$ of 0.1% was carried out on the reconstituted sample.

When considering the above, the sample disturbance of the FSs and the RSCLs of Tone-river sand by the low confining pressure during the thaw process can be explained as follows. Although contact forces between soil particles of the FSs were kept under the in-situ condition by freezing pore water, they would be released suddenly when the pore water around the soil particles is thawed. Although Koseki and Ohta (2001) showed that small strain characteristics obtained during isotropic loading and reloading were similar to each other, the above sudden reduction of the contact forces between soil particles seems to be a mechanism that is different from the one mobilized during the conventional isotropic unloading
Histories. Therefore, thawing at a confining pressure that is lower than the in-situ stress condition would cause the soil particles of the FSs to release suddenly the contact forces. The FSs of Tone-river sand could be disturbed easily by the low confining pressure during the thaw process because they had no cementation between soil particles, while Edo-river B and C sands had larger resistance due to the cementation effect against the disturbance.

Small Strain Characteristics during Isotropic Consolidation

In this study, in order to correct for the effects of different void ratios, the following function proposed by Hardin and Richart (1963) is applied to normalize the static Young’s moduli, $E_s$, and dynamic shear moduli, $G_d$.

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

Figures 22 and 23 shows the $E_s$ and $G_d$ values of Tone-river sand, respectively, measured during isotropic consolidation from 30 kPa to 100 kPa. In order to distinguish the results of the FSs and the RSs, the former results are shown in Figs. 22(a) and 23(a) while the latter results with the average values of the FSs are shown in Figs. 22(b) and 23(b). Data with thin lines and small dots represent the test results of individual specimens. Meanwhile, data with a circle symbol, a thick line and a broken line represent the average value of test results of the FSs thawed at 98 kPa, the FSs thawed at 30 kPa and the RSs, respectively.

Larger values of small strain stiﬁness were observed at larger stress levels. As shown in Figs. 22(a) and 23(a), the average values of static Young’s moduli, $E_s$, and dynamic shear moduli, $G_d$, of the FSs which had been thawed at 98 kPa were about 10 to 15% larger than those thawed at 30 kPa. Because the $G_d$ values of the FSs which were thawed at 98 kPa were almost similar to the results of the in-situ PS logging as shown in Fig. 23, it can be inferred that the disturbance of the FSs thawed at 98 kPa was very small. Tokimatsu and Hosaka (1986), Shibuya et al. (1995) and Chiara and Stokoe (2006) also reported that the quality of an undisturbed sample can be examined through comparison of shear modulus between in-situ and laboratory tests.

Note again that the liquefaction resistance of the FSs was larger than that of the RS, and that of the FS which was thawed at 30 kPa was smaller than that of the FS thawed at 98 kPa in the case of the Tone-river sand.
Therefore, the small strain characteristics, especially $G_d$, can be used to estimate a possible change in the liquefaction resistance of both the FS and the RS, and to identify the sample disturbance caused by the low confining pressure during the thaw process.

Figures 24 and 25 show the values of $E_s$ and $G_d$ of Edo-river B and C sands measured during isotropic consolidation. Data with thin lines and small dots represent the test results of individual specimens. Meanwhile, data with circle symbols, a thick line and a broken line represent the average value of the test results of the FSs thawed at 98 kPa, the FSs thawed at 30 kPa and the RSs, respectively. The average values of $E_s$ and $G_d$ of the FSs which had been thawed at 98 kPa were slightly larger than those thawed at 30 kPa. Although the $E_s$ values of the FSs of the Edo-river C sand thawed at 30 kPa were slightly larger than those of the FSs thawed at 98 kPa, the difference between them was relatively small. Note that the FSs of Edo-river C sand were thawed at a confining pressure that is lower than their in-situ overburden pressure. The sample disturbance of Edo-river B and C sands was probably small because the $G_d$ values of the FSs which were thawed at 98 kPa were almost similar to the results of in-situ PS logging as shown in Figs. 24(b) and 25(b).

The remarkable feature of the test results measured during isotropic consolidation was the differences in the $E_s$ and $G_d$ values, respectively, between the FSs and the RSs of each sample. The ratios of the average values of $E_s$ and $G_d$ of the RSs to those of the FSs which were thawed at 98 kPa, $E_s(RS)_{ave}/E_s(FS)_{ave}$ and $G_d(RS)_{ave}/G_d(FS)_{ave}$, measured at the end of isotropic consolidation are shown in Figs. 22(b), 23(b), 24 and 25. The values of $E_s(RS)_{ave}/E_s(FS)_{ave}$ and $G_d(RS)_{ave}/G_d(FS)_{ave}$ were 0.88 and 0.76 for Tone-river sand, 0.62 and 0.71 for Edo-river B sand, and 0.61 and 0.50 for Edo-river C sand, respectively. These results indicate that the difference in the small strain characteristics between the FS and the RS was the largest with Edo-river C sand. In addition, the difference with Edo-river B sand was larger than that with Tone-river sand. Since it would be reasonable to assume that the FSs from both the Holocene and Pleistocene deposits have their own aging effects while the RSs do not have such effects, the values of $E_s(RS)_{ave}/E_s(FS)_{ave}$ and $G_d(RS)_{ave}/G_d(FS)_{ave}$ reflect probably the degree of aging effects of each deposit. In other words, in this study, the aging effects of the FSs from the Pleistocene deposit were stronger than those from the Holocene deposit.

In addition to the above information, Figs. 22 to 25
show the mean values of the parameter, $m$, for the pressure-level dependencies of $E_s$ and $G_d$ defined by the equation as shown in the respective figures. Kohata et al. (1997) reported that the value of $m$ for cemented soils were generally smaller than those for un cemented granular soils. The difference in the $m$ values for $G_d$ between the FS and the RS suggested development of cementation between soil particles for the FSs: especially with Edo-river C sand. However, it was difficult to distinguish quantitatively the effects of the inter-locking from those of the cementation based on the values of $E_s$ and $G_d$. More detailed investigations are required on these issues.

**DISCUSSIONS**

In this study, the extent of the aging effect influenced the sample disturbance caused by the low confining pressure during the thaw process and the liquefaction properties. In addition, the small strain characteristics reflected the difference in the aging effects between Holocene and Pleistocene deposits.

Table 2 summarizes the liquefaction resistance, $R_{L15}$, which is defined as the cyclic stress ratio to cause $e_{DA} = 3\%$ in 15 cycles, the average values of the static Young's moduli, $E_s$, and the dynamic shear moduli, $G_d$, which are measured immediately before the liquefaction test, and the unconfined compression strength, $q_u$, of the FSs. Figure 26 shows the relationships between the ratios of $E_s$, $G_d$, and $R_{L15}$ values for the FSs thawed at 30 kPa with respect to those for the FSs thawed at 98 kPa.

In the case of the Tone-river sand, the values of $R_{L15}$, $E_s$, and $G_d$ decreased by approximately 14%, 7% and 14%, respectively, when the FSs were thawed at 30 kPa in comparison with those thawed at 98 kPa. On the other hand, the reductions in the values of $R_{L15}$, $E_s$, and $G_d$ due to the low confining pressure were not more than 8% in the case of Edo-river B and C sands (except for the $E_s$ value of Edo-river C sand). This difference in the values of $R_{L15}$, $E_s$, and $G_d$ between the Holocene and the Pleistocene deposits was due possibly to different degrees of sample disturbance during the thaw process. Specifically, the degree of sample disturbance was small with the Pleistocene deposits which would have the cementation effect, while that of the Holocene deposit which would not have such an effect became higher.

It should be noted that the effect of sample disturbance on the liquefaction resistance caused by the low confining pressure was not large in this study (reduction in $R_{L15}$ by 15% at maximum). However, more significant effect on the test results may be observed if the frozen sample was exposed to the normal temperature during the sample preparation. Therefore, the authors recommend that the FSs, especially those retrieved from Holocene deposits which were frozen at the field, should be thawed at the same confining pressure as the in-situ stress condition. In addition, during the thaw process, the volume of the specimen changed rapidly under the normal temperature as shown in Figs. 6 to 9. Hence, the preparation of the specimen before applying a certain level of confining pressure should be carried out under an atmospheric temperature that is lower than the thawing point of the pore water.

**CONCLUSIONS**

The present paper consists of comparison of small strain characteristics and liquefaction resistances of three kinds of in-situ frozen samples (FSs) which were taken from deposits of different ages, and their reconstituted samples with/without stress history (RSs, RSCLs). The test results could be summarized as follows;

a) The volume change of FSs was affected by the level of the confining pressure during the thaw process, while the difference in the residual volumetric strain at the end of isotropic consolidation was insignificant.
b) The volume of the specimens rapidly decreased during the thaw process under a normal temperature, and the peak value of volumetric strain was observed in one hour after the start of thawing.

c) Large differences in the small strain stiffness between the FSs and the RSs, which would reflect the extents of natural aging effects, were observed during the isotropic consolidation stage of Edo-river B and C Pleistocene sands, while the difference with Tone-river Holocene sand was relatively small.

d) From the result of unconfined compression tests, the existence of cementation effect between soil particles were confirmed with the FSs of Edo-river B and C Pleistocene sands, while it was not observed with the FS of Tone-river Holocene sand and the RSCL of Edo-river C Pleistocene sand.

e) Decreases in small strain stiffness during isotropic consolidation and liquefaction resistance, which were caused by sample disturbance during the thaw process, were observed in the FSs of Tone-river Holocene sand and the RSCLs that were thawed at a confining pressure that was lower than the in-situ overburden pressure.

f) The extent of the reductions in the small strain characteristics and liquefaction resistance were relatively small with the FSs of Edo-river B and C Pleistocene sands even if the FSs were thawed at the lower confining pressure.

g) The above features suggest that the sample disturbance caused by the lower confining pressure during the thaw process was influenced by the extent of the cementation effect of the specimen, and it could be identified based on the small strain characteristics that were evaluated by static and dynamic measurements.

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