EFFECTS OF DIFFERENT CONSOLIDATION CONDITIONS ON LIQUEFACTION RESISTANCE AND SMALL STRAIN QUASI-ELASTIC DEFORMATION PROPERTIES OF SANDS CONTAINING FINES

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ABSTRACT

In order to investigate the effects of different consolidation conditions on liquefaction characteristics of sands containing fines, a series of undrained cyclic triaxial liquefaction tests was performed on artificial samples prepared by mixing Toyoura sand and bentonite at a ratio of 95% to 5% by dry weight. Some specimens were isotropically consolidated for 1, 20 or 100 days at a regular temperature, while the others were consolidated for 2 or 5 days while heating the cell water up to 60 degrees centigrade. Over-consolidated specimens with OCR of 2 and 4 were also prepared at a regular temperature. During consolidation and cyclic triaxial shearing of several specimens, their quasi-elastic deformation properties were measured while applying very small amplitude cyclic axial loads. Longer consolidation time, higher temperature during consolidation or higher ratio of over-consolidation resulted in an increase in the liquefaction resistance, with the exception that the liquefaction resistance of specimens consolidated for 100 days was not larger than that of specimens consolidated for 20 days. On the other hand, such different consolidation conditions affected the change in the quasi-elastic deformation properties in different manners. Development of cementation was suggested to have occurred during consolidation under high temperature. Reduction in the extent of anisotropy was suggested to have occurred during over-consolidation, which was accompanied by a decrease in the negative dilatancy at the initial part of shearing.

Key words: consolidation conditions, fines, liquefaction, sand, triaxial test, Young's modulus (IGC: D6/D7)

INTRODUCTION

Effects of fines content on liquefaction characteristics of sands have been one of the major issues in the field of geotechnical earthquake engineering (Ishihara et al., 1977; Ishihara and Koseki, 1989; Prakash et al., 1998). However, there still exists a discrepancy between the field performances and the laboratory test results. In general, natural sand deposits containing fines are less prone to cause liquefaction-induced damage to structures than clean sand deposits, while their liquefaction resistances measured in the laboratory on reconstituted samples are comparable to those of clean sands. In relation to these aspects, based on laboratory tests (Goto, 1994) and case studies (Yasuda et al., 1994), it has been reported that aging due to long-term consolidation may largely affect the liquefaction resistance of sands containing fines.

On the other hand, the combined effects of aging and fines content on the liquefaction characteristics of sands have not been fully understood. In addition, it has been reported that the increase in the liquefaction resistance due to long-term consolidation was equivalent to that obtained by over-consolidation (Tatsuoka et al., 1988).

Attempts have also been made to reproduce the aging effects in a shorter time by consolidating the specimen at high temperature (Goto, 1994). However, effects of over-consolidation and those of consolidation at high temperature on liquefaction resistance have not been fully understood either.

In view of the above, a series of undrained cyclic triaxial liquefaction tests on artificial samples containing 5% of clay fractions by dry weight was performed in the present study, while changing consolidation conditions with respect to the period of consolidation, the temperature during consolidation and the ratio of over-consolidation. An attempt was also made to estimate the change in the structure of soil particles, possibly caused by these different consolidation conditions, through measurement of quasi-elastic deformation properties while applying very small amplitude cyclic axial loads during some of the tests. This test series is an extension of the previous investigation reported by Koseki et al. (1999).

APPARATUS AND TESTING PROCEDURES

Two types of triaxial testing apparatus were employed:

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Written discussions on this paper should be submitted before July 1, 2002 to the Japanese Geotechnical Society, Sugayama Bldg. 4F, Kanda Awaji-cho 2-23, Chiyoda-ku, Tokyo 101-0063, Japan. Upon request the closing date may be extended one month.

one loaded axially using an AC servo-motor (Santucci de Magistris et al., 1999), and the other loaded axially using a conventional air cylinder. The former apparatus was employed in some tests to evaluate the change in the quasi-elastic deformation properties by applying cyclic axial loads at an axial strain amplitude of about 10^{-5} (hereafter denoted as small cyclic loading). During small cyclic loading, the vertical displacement of the top cap was measured with a proximity transducer (gap sensor) having a capacity of 2 mm. For both types of apparatus, the top and bottom ends of the specimen, 150 mm in height and 75 mm in diameter, were not lubricated, but porous stones having the same diameter as the specimen were employed. Under the above testing conditions, effects of bedding error were estimated to be negligible based on relevant triaxial test results on the Toyoura sand that was used as the base material in the present study (see Fig. 7 of Koseki et al., 1998). Figure 1 shows typical stress-strain relationship and effective stress path measured during small cyclic loading in the course of undrained cyclic triaxial liquefaction tests (denoted as large cyclic loading, refer to Fig. 2).

The tested sample ($e_{\max}=0.975$, $e_{\min}=0.561$) was prepared artificially by mixing Toyoura sand and bentonite (Natrium-based bentonite produced at Tsukifu Mine in Yamagata prefecture, Japan, $w_L=357\%$, $w_P=25.1\%$) at a ratio of 95% to 5% by dry weight. In order to enhance

the effects of fine contents on liquefaction resistance, bentonite was chosen as the artificial fines, referring to test results by Ishihara and Koseki (1989) who examined the effects of adding either bentonite, kaolinite, mica or volcanic ash clay to Toyoura sand.

A solid cylindrical specimen, at a relative density about 50%, was prepared by putting the sample at a water content of 5% in a metal mold, which was located on the pedestal of the triaxial cell, and by tamping it in ten layers with a cylindrical metal mass. To prepare each layer, a required amount of soil was tamped into a specified thickness by pushing its surface manually with a metal cylinder having a diameter of 3.4 cm; it had a mechanical lock so that the cylinder would not excessively penetrate into the soil. It should be noted that the relative density of specimens after consolidation was in the range of 47 to 56%, which was not very different among different consolidation conditions (refer to Table 1).

After saturating the specimen by the double vacuuming method applying a pore water pressure of -90 kPa and a cell pressure of either -80 or -60 kPa (Ampadu and Tatsuoka, 1993), it was isotropically consolidated up to confining stress of $\sigma'_v = \sigma'_h = 100$ kPa, where σ'_v and σ'_h denote effective vertical (or axial) and horizontal (or radial) stresses, respectively. The confining stress during the saturation process was set to 10 kPa for tests where the change in the quasi-elastic deformation properties

Fig. 1. Typical test results measured during small cyclic loading in undrained large cyclic loading: a) stress-strain relationship and b) effective stress path

Fig. 2. Typical test results measured during undrained large cyclic loading: a) stress-strain relationship and b) effective stress path

Table 1. Conditions of consolidation

Symbol in Fig. 4	Temperature	Period	OCR	Dr after consolidation
▲	60°C	2 days	1	47–50%
■	60°C	5 days	1	52–54%
□	Regular	1 day	1	50–54%
○	Regular	20 days	1	51–52%
◻	Regular	100 days	1	49–52%
▽	Regular	1 day	2	48–52%
△	Regular	1 day	4	51–56%

was measured, while it was set to 30 kPa for the other tests.

Conditions of consolidation employed in the present study are summarized in Table 1. In some tests, the cell water was heated up to a maximum of 60 degrees centigrade during consolidation for about 2 or 5 days, as typically shown in Fig. 3(a), and was then restored to the regular temperature (about 20 degrees centigrade). To heat the cell water uniformly, a 100-watt ribbon-shaped flexible heater (coated with silicone-rubber, 12 mm wide, 3 mm thick, 2 m in total length) was installed in the triaxi-

al cell so that it wrapped three vertical steel rods supporting the top plate; it was controlled automatically while monitoring the cell water temperature.

In the other tests, the cell water was maintained at the regular temperature, but the consolidation period was varied to 1, 20 or 100 days. In some of the latter tests with a consolidation period of 1 day, specimens were subjected to over-consolidation at an over-consolidation ratio (denoted as OCR) of 2 or 4, as schematically shown in Fig. 3(b). Since the cell water starts to penetrate the membrane into the specimen after about 100 hours (Tatsuoka et al., 1988), in order to maintain the saturation degree of cell water during the long-term consolidation for 20 or 100 days, the triaxial cell was completely filled with de-aired water, and olive oil was used at the air-water interface in the burette connected to the triaxial cell. It was found, however, that the B value of the specimen during and after the long-term consolidation became smaller than the target value of 0.96. Therefore, the specimen had to be re-saturated by circulating de-aired water at several stages during and after the long-term consolidation. Prior to undrained large cyclic loading, a part of the cell water was removed to allow for large deformation of the specimen.

When the apparatus with the AC servo-motor was employed, the confining stress was reduced to 10 kPa after consolidation and then restored to 100 kPa (refer to Fig. 3(b)). During these isotropic unloading and reloading processes as well as the initial isotropic loading process before consolidation, small cyclic loadings were applied under both drained and undrained conditions after some drained aging (about 10 minutes) at several stress states, which were conducted for comparison with the results of small cyclic loadings applied during the loading process before consolidation.

After consolidation, the B value of all the specimens was measured and confirmed to be greater than 0.96. Then, undrained large cyclic loading with a constant amplitude of cyclic axial stress while keeping the cell pressure constant was applied either by the air cylinder with an input of sinusoidal waves at a frequency of 0.1 Hz, or by the AC servo-motor with an axial strain rate of about 0.2%/min. When the AC servo-motor was employed, small cyclic axial loadings under undrained condition were applied with an axial strain rate of about 0.02%/min at several stress states in the course of the large cyclic loading without any pause (i.e., without aging).

RESULTS AND DISCUSSION

Liquefaction Resistance

Figure 4 shows relationships between the cyclic stress ratio $\sigma_d/(2\sigma'_0)$ and the number of cycles N_c to cause a double amplitude axial strain ε_{DA} of 5 or 10%, where σ_d and σ'_0 denote the single amplitude cyclic axial stress and the confining stress immediately before applying the large cyclic loading ($=100$ kPa), respectively. It can be seen that results of specimens consolidated for 100 days showed relatively large scattering. In relation to this, dar-

Fig. 3. a) Typical change in measured cell water temperature for consolidation at high temperature and b) schematic change in confining stress for over-consolidation

Fig. 4. Relationships between cyclic stress ratio and number of cycles to cause double amplitude axial strain of a) 5% and b) 10%

kening in the color of specimens was observed partially through the membrane in the course of the consolidation for 100 days, which was confirmed after each test in retrieving the tested specimen. Although no other evidence could be observed, it was estimated that a chemical and/or biological reaction took place during the long-term consolidation. The extent of such a reaction may have been different among different specimens, possibly causing the relatively large scattering in their liquefaction resistances.

It should be noted that, for a consolidation period of 20 days, results from the previous test series by Koseki et al. (1999) are plotted in Fig. 4 to compare with those obtained in the present study. In the figure, the former and the latter data are plotted as circles with and without double asterisks, respectively. It can be seen that the results from these two test series exhibited some discrepancy. Reasons for this discrepancy are not known to the authors, but the aforementioned chemical/biological reaction may have affected the results from the present study even during the consolidation for 20 days. In the following comparison, therefore, liquefaction resistance under a consolidation period of 20 days was evaluated based on the results from the previous test series.

Fig. 5. Change in normalized liquefaction resistance with a) consolidation period and b) over-consolidation ratio

Based on Fig. 4(b), values of $\sigma_d/(2\sigma'_0)$ to cause ϵ_{DA} of 10% in ten cycles were evaluated as the liquefaction resistance and were normalized with the reference value that was obtained for a consolidation period of 1 day at the regular temperature and at OCR=1. These normalized liquefaction resistances (denoted as R) are plotted versus the consolidation period in Fig. 5(a), where relevant results from the previous test series by Koseki et al. (1999) are also shown. It can be seen that the liquefaction resistance increased by about 20% when the consolidation period was extended from 1 day to 20 days. When compared to the results by Tatsuoka et al. (1988), this increment was consistent with that obtained on Sengeniyama sand containing 2.4% of fines in weight, while it was larger than those on other clean sands. Future investigations are, however, required on the effects of much longer consolidation periods, since reduction in the liquefaction resistance for the consolidation period of 100 days was observed in the present study, as can be seen from Fig. 5(a).

It can also be seen from Fig. 5(a) that specimens consolidated at the higher temperature of 60 degrees centigrade showed larger increases in liquefaction resistance with respect to the effects of the consolidation period. This tendency is consistent with the results by Goto (1994) on a mixture of Toyoura sand and marine clay at a

ratio of 80% to 20% by dry weight. In Fig. 5(a), results from the previous test series by Koseki et al. (1999) are also shown, and it can be seen that specimens consolidated for 1 day at higher temperatures exhibited larger liquefaction resistance. These results suggest the possibility of consolidation at high temperature simulating the aging effects due to long-term consolidation on sands containing fines with respect to the liquefaction resistance.

Similar comparisons were made in Fig. 5(b) with respect to the effects of over-consolidation ratio (OCR) on the liquefaction resistance. The liquefaction resistance increased by about 20% and 40% when the specimens underwent over-consolidation at OCR=2 and 4, respectively. These increments are smaller than those from a previous study by Ishihara and Takatsu (1979) on Fuji river sand in which the R values increased in proportion to the square-root of OCR (refer to the curve of $R = \text{OCR}^{0.5}$ shown in Fig. 5(b)), but are consistent with the test results on Toyoura sand by Tatsuoka et al. (1988) and Yamashita et al. (1997) where, when the relationship between R and OCR was approximated as $R = \text{OCR}^n$, the n value of Toyoura sand was about 0.25 or smaller.

On the other hand, it should also be noted that the existence of fine contents may affect the n value defined above. Yamashita et al. (1997) reported that the n values of different sands containing fines, including a mixture of Toyoura sand and Kaolinite at a ratio of 95% to 5%, or 90% to 10%, by dry weight, were about 0.5 or larger. Similar effects of fine contents on the liquefaction resistance of over-consolidated specimens had been reported by Ishihara et al. (1977) as well.

In Fig. 5(b), values of $\sigma_d/(2\sigma'_v)$ to cause ε_{DA} of 5% in twenty cycles were also plotted to compare the present test results with those obtained by Yamashita et al. (1997) under the same definition of liquefaction resistance. In the present study, however, the increments in the R values due to over-consolidation were not largely affected by the different definitions of liquefaction resistance.

Quasi-Elastic Deformation Properties under Isotropic Stress States

Values of the drained vertical Young's modulus E_v that were measured during initial isotropic loading process before consolidation and during isotropic unloading and reloading processes after consolidation are compared in Fig. 6. In order to account for the variation in the void ratio e during each test, the E_v values were divided by the void ratio function of $f(e) = (2.17 - e)^2 / (1 + e)$, referring to Hardin and Richart (1963). In these figures, test results consolidated for 20 or 100 days are not shown, since the aforementioned chemical/biological reaction may have affected the results.

In Fig. 6(a), the observed relationships between $E_v/f(e)$ and $\sigma'_v (= \sigma'_h)$ for a specimen consolidated at OCR=1 for 1 day, that were plotted on logarithmic scales, were not largely different among the different processes.

As shown in Fig. 6(b), the observed relationships between $E_v/f(e)$ and σ'_v for a specimen consolidated for 1

Fig. 6. Drained vertical Young's moduli measured under isotropic stress states on specimens consolidated for 1 day at regular temperature at a) OCR=1, b) OCR=2, c) OCR=4, and d) for 5 days at high temperature at OCR=1

day at $\text{OCR}=2$ (i.e., at $\sigma_v' = 200$ kPa) were not largely different among the different processes, similarly to the case with consolidation for 1 day at $\text{OCR}=1$. On the other hand, as shown in Fig. 6(c), for a specimen consolidated at $\text{OCR}=4$ (i.e., at $\sigma_v' = 400$ kPa), an increase in the values of $E_v/f(e)$ at the same stress state was observed after consolidation, and they were not reduced in the course of isotropic unloading.

As shown in Fig. 6(d), the behavior of a specimen consolidated for 5 days at high temperature was similar to that of the specimen consolidated at $\text{OCR}=4$. However, when the pressure-level dependency of E_v (i.e., the slope m of the relationships between logarithms of $E_v/f(e)$ and σ_v' values, as indicated in Fig. 6) was compared, it remained almost the same for the specimen consolidated at $\text{OCR}=4$, whereas it decreased for the specimen consolidated at high temperature. Since the pressure-level dependencies of E_v for cemented soils were generally smaller than those for uncemented granular soils as reported by Kohata et al. (1997), development of cementation between soil particles was suggested to have occurred during consolidation at high temperature in the present study, but not during consolidation at $\text{OCR}=4$. Further investigations are required on these issues.

In order to compare the change in the quasi-elastic behaviors caused by different consolidation conditions in detail, the ratios of the undrained and drained vertical Young's moduli $E_{v,u}/E_v$, which were measured by applying small cyclic loading under undrained and drained conditions, respectively, were plotted versus σ_v' ($=\sigma_h'$) in Fig. 7. Theoretical relationships between $E_{v,u}/E_v$ and σ_v' , which were obtained based on the cross-anisotropic elastic formulation proposed by Tatsuoka et al. (1999) considering effects of inherent and stress-induced anisotropies and those of membrane penetration (denoted as MP), are also shown in the figure; the parameter a represents the degree of inherent anisotropy ($=E_v/E_h$ under isotropic stress state); the parameter v_0 denotes a reference Poisson's ratio; and the effects of MP on the tested specimens of mixture of Toyoura sand and bentonite were assumed to be the same as those on specimens of Toyoura sand. Refer to Koseki et al. (1998, 1999, 2000) for the details of the theory and its verification.

It can be seen from Fig. 7(a) that, for the specimen consolidated at $\text{OCR}=4$, the $E_{v,u}/E_v$ values measured at the same σ_v' value after consolidation became larger than those measured before consolidation. Such a change could be simulated by the theory by reducing the value of the parameter a from 1.2 to 1.0 and that of the reference Poisson's ratio v_0 from 0.2 to 0.15, while correcting for the effects of MP. On the other hand, for the specimen consolidated at high temperature, no remarkable change in the relationships between $E_{v,u}/E_v$ and σ_v' was observed in Fig. 7(b), and they could be simulated by setting $a=1.2$ and $v_0=0.2$ with correction for MP effects. It should be noted that these values of a and v_0 were set as results from trial and error simulations, since no relevant test results on these values was available.

Based on the above different behaviors, reduction in

Fig. 7. Ratios of undrained and drained vertical Young's moduli under isotropic stress states on specimens consolidated a) for 1 day at regular temperature at $\text{OCR}=4$, and b) for 5 days at high temperature at $\text{OCR}=1$

the extent of anisotropy of quasi-elastic properties, possibly with change in the reference Poisson's ratio, was suggested to have occurred during consolidation at $\text{OCR}=4$, but not during consolidation at high temperature. When subjected to isotropic consolidation under high confining stress, it would be reasonable to expect a certain loss of anisotropy due to extensive change in the soil structure. On the other hand, possible development of cementation during consolidation at high temperature would not result in a remarkable change of anisotropy, since the soil structure would not change largely. More detailed investigations are required to confirm these issues.

Comparison of Behaviors during Undrained Large Cyclic Loading

From the undrained vertical Young's moduli $E_{v,u}$ measured at several stress states during undrained large cyclic loading, values of the drained vertical Young's moduli E_v were estimated based on the theoretical relationships between $E_{v,u}/E_v$ and σ_v' shown in Fig. 7 by using a combination of parameters that could simulate the behavior observed during isotropic reloading after consolidation (i.e., $a=1.0$, $v_0=0.15$ with correction for MP effects for

Fig. 8. Drained vertical Young's moduli estimated based on undrained vertical Young's moduli during undrained large cyclic loading on specimens consolidated a) for 1 day at regular temperature at OCR=4, and b) for 5 days at high temperature at OCR=1

the specimen consolidated at OCR=4, and $a=1.2$, $v_0=0.2$ with correction for MP effects for the specimen consolidated under high temperature). They were divided by the void ratio function and are plotted versus σ'_v in Fig. 8. For reference, data measured during isotropic reloading after consolidation are also shown in the figure.

When compared at the same σ'_v value, it can be seen from Fig. 8(a) that, for the specimen consolidated at OCR=4, the $E_v/f(e)$ values during large cyclic loading were smaller than those during isotropic reloading. This degradation in the $E_v/f(e)$ values was caused by damage to the soil structure due to the large cyclic loading. In particular, the degradation proceeded at the early stage of the cyclic loading before the σ'_v value started to decrease due to the accumulation of excess pore water pressure (i.e., when the σ'_v value was about 100 kPa). On the other hand, for the specimen consolidated at high temperature shown in Fig. 8(b), the degradation in the $E_v/f(e)$ values was to a lesser extent than that for the specimen consolidated at OCR=4, and it proceeded gradually in the course of the decrease in the σ'_v value.

It should be noted that, in Figs. 8(a) and 8(b), no significant difference could be observed between the behaviors measured under triaxial compression condition (i.e.,

Fig. 9. Relationships between estimated drained vertical Young's modulus and effective vertical stress during undrained large cyclic loading on specimens subjected to a) over-consolidation and b) high-temperature consolidation

$\sigma'_v > \sigma'_h$) and those measured under triaxial extension condition (i.e., $\sigma'_h > \sigma'_v$). This trend was different from that observed on specimens of Toyoura sand, for which the degradation in the $E_v/f(e)$ values under triaxial compression condition was smaller than that under triaxial extension condition, as reported by Koseki et al. (1998, 2000). These different trends are possibly affected by different procedures of specimen preparation as well as the different composition of the tested materials.

In order to investigate the effects of different consolidation conditions on the quasi-elastic behaviors, the relationships between $E_v/f(e)$ and σ'_v observed during large cyclic loading are compared in Fig. 9. For reference, the relationships observed during isotropic reloading after consolidation are compared in Fig. 10. It should be noted that, in order to estimate the E_v values shown in Fig. 9 based on the theoretical relationships, the combination of parameters that was used in preparing Fig. 8(b) for the specimen consolidated under high temperature (i.e., $a=1.2$, $v_0=0.2$ with correction for MP effects) was employed for other specimens except for the one consolidated at OCR=4, since their behaviors observed during isotropic reloading after consolidation could be reasonably simulated by using this combination.

It should also be noted that values of dp'/dq meas-

Fig. 10. Relationships between drained vertical Young's modulus and effective vertical stress during isotropic reloading on specimens subjected to a) over-consolidation and b) high-temperature consolidation

ured during undrained small cyclic loading in the course of the large cyclic loading that correspond to the direction of effective stress path as shown in Fig. 1(b), in particular those measured under triaxial compression condition, could be reasonably simulated by the theory based on the cross-anisotropic elastic formulation (refer to Fig. 17 of Koseki et al., 1999). In addition to the consistency between the theory and the behaviors observed during isotropic consolidation shown in Fig. 7, this also verifies the theory and validates the procedure employed above to estimate drained vertical Young's moduli from undrained ones that were measured in the course of the large cyclic loading.

It can be seen from Fig. 10(a) that, after consolidation at $\sigma_v' = 400$ kPa (i.e., OCR=4), the E_v value at the same σ_v' value during isotropic reloading became larger than that after consolidation at $\sigma_v' = 100$ kPa (OCR=1) or 200 kPa (OCR=2). During large cyclic loading, however, the E_v values shown in Fig. 9(a) were not largely different among different consolidation conditions. It was, therefore, inferred that effects of over-consolidation at OCR=4 on quasi-elastic properties disappeared at the early stage of the large cyclic loading, as can be seen from Fig. 8(a) as well.

Regarding the effects of high-temperature consolida-

Fig. 11. Comparison of effective stress paths in first quarter cycle of undrained large cyclic loading

tion, the deviation and the order in the values of E_v at the same σ_v' value among different specimens in Fig. 9(b) were not largely different from those shown in Fig. 10(b). On the other hand, when compared in detail, high-temperature consolidation resulted in smaller pressure-level dependency of E_v values during large cyclic loading as well as isotropic reloading. The latter behavior suggests that the effects of high-temperature consolidation, possibly due to development of cementation as mentioned on Fig. 6(d), did not disappear even during large cyclic loading. It should be noted that, due to the possible deterioration during long-term consolidation mentioned before, or to a different extent of heterogeneity among different specimens, or both, the E_v values deviated among different specimens consolidated for different periods, and such an effect did not disappear during large cyclic loading.

In order to compare the dilatancy characteristics at the early stage of the large cyclic loading, typical effective stress paths during the first quarter cycle are shown in Fig. 11; which were measured on specimens tested with the AC servo-motor. Note that in some tests the effective stress path did not start exactly from an isotropic stress state, due possibly to a delay in recording the data at the beginning of shearing. The extent of negative dilatancy can be evaluated from the observed reduction in the effective mean principal stress $p' = (\sigma_v' + 2\sigma_h')/3$ during shearing. It was largest for the specimen consolidated for 1 day at OCR=1, followed by the specimens consolidated for 5 days at high temperature, and for 1 day at OCR=2, respectively, and was smallest for the specimen consolidated for 1 day at OCR=4. This order was consistent with the order of the liquefaction resistance shown in Figs. 4 and 5; i.e., specimens that exhibited larger negative dilatancy at the early stage of the large cyclic loading had smaller liquefaction resistance.

On the other hand, as shown in Fig. 12, no clear correlation could be found, except for the specimen consolidated at OCR=4, between the order of the liquefaction resistance and that of the E_v value measured at the end of isotropic reloading after consolidation. Similar results

Fig. 12. Relationships between liquefaction resistance and drained vertical Young's modulus measured at end of isotropic reloading

were obtained by Teachavorasinskun et al. (1994) on Toyoura sand with respect to effects of cyclic prestraining applied before large cyclic loading. Note that, as mentioned before in Figs. 8(a) and 9(a), the E_v value of the specimen consolidated at OCR=4 degraded rapidly at the early stage of the large cyclic loading and became similar to those of other specimens consolidated at OCR=1 or 2. In the present study, therefore, change in the liquefaction resistance due to consolidation at high temperature or over-consolidation was not directly linked with the change in the E_v value. However, as mentioned before, from the change in the pressure-level dependency of the E_v value, possible development of cementation at high-temperature consolidation could be inferred, which may have contributed to the increase in the liquefaction resistance.

CONCLUSIONS

The test results from the present study on artificial samples prepared by mixing Toyoura sand and bentonite at a ratio of 95% to 5% by dry weight can be summarized as follows.

The liquefaction resistance increased by about 20% when the consolidation period was extended from 1 day to 20 days. Under the same consolidation period of 1 day, it increased by about 20% and 40% when specimens underwent over-consolidation at OCR=2 and 4, respectively. Specimens consolidated at a higher temperature of 60 degrees centigrade showed a larger increase in liquefaction resistance with respect to the effects of the consolidation period. On the other hand, specimens consolidated for 100 days did not show any increase in liquefaction resistance, due possibly to some sort of chemical/biological reaction of specimens evidenced by the partial darkening of their colors observed during the long-term consolidation.

Based on the change in the pressure-level dependency of the quasi-elastic properties under isotropic stress

states, development of cementation between soil particles was suggested to have occurred during consolidation at high temperature, but not during consolidation at OCR=4. On the other hand, reduction in the extent of anisotropy of quasi-elastic properties was suggested to have occurred during consolidation at OCR=4, but not during consolidation at high temperature.

Based on the change in the quasi-elastic properties observed during large cyclic loading, it was inferred that effects of over-consolidation at OCR=4 disappeared at the early stage of the large cyclic loading, while those of high-temperature consolidation did not disappear even during the large cyclic loading.

Specimens that exhibited larger negative dilatancy at the early stage of the large cyclic loading had smaller liquefaction resistance. On the other hand, change in the liquefaction resistance was not directly linked with the change in the vertical Young's modulus, with the exception of the change in the pressure-level dependency as mentioned above, which may have contributed to the increase in the liquefaction resistance.

ACKNOWLEDGEMENTS

The authors appreciate Dr. S. Goto, Shimizu Corporation, for his valuable suggestions on testing conditions under high-temperature. They also wish to thank Mr. N. Maeshiro, Electric Power Development Company Limited, and Mr. T. Sato, Port and Airport Research Institute, and Dr. K. Hayano, Institute of Industrial Science, University of Tokyo, for their help in conducting the tests.

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