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\textbf{ABSTRACT}

Studies in the past showed that the laboratory tests on dense sand specimens obtained by the conventional tube sampling method may exhibit lower liquefaction resistance than the field strength observed in situ. This phenomenon would result in excessive over-design of important infrastructures on such dense sandy ground. Therefore, in this study, a series of cyclic undrained hollow cylindrical torsional shear tests were conducted on sand specimens that were prepared by air-pluviation method with high initial relative density (around 80\%), with several attempts to reach high liquefaction resistance. During these torsional shear tests, different kinds of pre-shear histories were applied before cyclic loading. The test results showed that specimens with pre-shear using small strain amplitude could exhibit significantly high liquefaction resistance, as compared to the one without the pre-shear.

\textbf{Keywords:} dense sand specimen, liquefaction, pre-shear history

\section{1 INTRODUCTION}

In the past, the study of liquefaction was mainly focused on young sandy deposits or loose sandy ground where liquefaction resistance was thought to be low. However, during the construction of essential facilities like the nuclear power plants, it is also of great importance to evaluate the liquefaction resistance even on dense sand layers. Therefore, in order to study the behavior of dense sandy ground, it is necessary to obtain samples that have the same or similar behavior as the in-situ sandy ground.

In the laboratory tests, Yoshimi et al. (1984) and Kiyota et al. (2009) reported that the liquefaction resistance of the in-situ frozen sample was significantly higher than that of tube samples and laboratory reconstituted samples. This difference was thought to be caused by the disturbance during the tube sampling method as well as the long period aging effect that the reconstituted samples did not experience. Therefore, the frozen sampling method is thought to be the best way to investigate the real liquefaction behavior. However, due to the high cost of the frozen sampling method, it is reasonable to find ways that can reproduce samples that have similar behavior as the in-situ ground.

In the past, Ishihara and Okada (1978) and Goto and Towhata (2014) reported that liquefaction resistance was influenced by pre-shear histories. Therefore, in this study, in order to simulate the aging effect and reach high liquefaction resistance, a series of undrained cyclic torsional shear tests were conducted with applying several kinds of pre-shear histories on sand specimens prepared with silica sand. In addition, the effects of different kinds of pre-shear histories were discussed based on the liquefaction behavior and repeated liquefaction behavior of those sand specimens.

\section{2 TESTING METHOD}

In this study, the hollow cylindrical torsional shear apparatus was applied, and its schematic figure is shown in Figure 1.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{test_apparatus.png}
\caption{Schematic figure of the test apparatus.}
\end{figure}
Although this test apparatus is originally a strain-controlled type, stress-controlled tests were performed by reversing the loading direction when a predetermined cyclic shear stress $\tau_{\text{cyc}}$ was reached.

Silica sand #7 was used as the test material and its particle characteristics and particle size distribution curve are shown in Table 1 and Figure 2.

Table 1. Particle characteristics of silica sand #7.

| Characteristic          | Value     |
|-------------------------|-----------|
| Soil particle density, $\rho_s$ | 2.648 g/cm$^3$ |
| Mean particle size, $D_{50}$    | 0.2 mm    |
| Maximum void ratio, $e_{\text{max}}$ | 1.210 |
| Minimum void ratio, $e_{\text{min}}$ | 0.700 |
| Fines content, $F_c$            | 0%        |

![Fig. 2. Grain size distribution of silica sand #7.](image)

The hollow cylindrical specimen was prepared by the air-pluviation method to reach the initial relative density ($D_r$) around 78~80% with the outer diameter of 200 mm, the inner diameter of 120 mm and the height of 300 mm. Then the specimen was fully saturated by the double vacuum method with the B value checked higher than 0.98. After saturation, the specimen was consolidated under an isotropic condition with the effective stress ($\sigma'_0$) of 100 kPa and the backpressure of 200 kPa. Then the cyclic torsional shear was conducted until the double amplitude of shear strain reached 2%. Like the procedure of repeated liquefaction test, reconsolidation and repeated cyclic loading with the same shear strain were carried out repeatedly. Therefore, as shown in Figure 4, the test was started with an initial relative density of 71.8% and after the relative density of 79% by applying pre-shear histories introduced above, the liquefaction test was conducted with the cyclic stress ratio of 1.0.

![Fig. 3. Time history of the shear strain of pre-shear under drained condition.](image)

![Fig. 4. Changes of relative density in pre-shear stages.](image)

In the case of applying pre-shear histories, the pre-shear history was only applied after the initial isotropic consolidation. In all the cases except for Test B-10, the specimen was subjected to repeated liquefaction tests 3 to 5 times with the same CSR.

For cases with pre-shear under drained condition (Test B-6~B-8), cyclic loading was applied with the specific double amplitude of shear strain for 100 cycles or more. An example of the time history of shear strain for this kind of pre-shear is shown in Figure 3.

In all the cases except for Test B-10, the specimen was subjected to repeated liquefaction tests 3 to 5 times with the same CSR. In the case of applying pre-shear histories, the pre-shear history was only applied after the initial isotropic consolidation. In all the cases except for Test B-10, the specimen was subjected to repeated liquefaction tests 3 to 5 times with the same CSR.

In one of the cases with pre-shear history under undrained condition (Test B-9), the pre-shear stage consists of several isolated undrained cyclic loading stages. In these stages, cyclic torsional shear was conducted until the double amplitude of shear strain reached 2%. Like the procedure of repeated liquefaction test, reconsolidation and repeated cyclic loading with the same shear strain were carried out repeatedly. Therefore, as shown in Figure 4, the test was started with an initial relative density of 71.8% and after the relative density of 79% by applying pre-shear histories introduced above, the liquefaction test was conducted with the cyclic stress ratio of 1.0.

![Fig. 5. Time history of the excess pore water pressure ratio in one of the pre-shear stages.](image)
loading was conducted under the control of the excess pore water pressure ($\Delta u$) generated during cyclic loading instead of the 2% double amplitude of shear strain. In each pre-shear stage, cyclic loading was conducted until the excess pore water pressure ratio ($\Delta u/\sigma_0'$) reached 0.5. The time history of the excess pore water pressure ratio in one of the pre-shear stages is shown in Figure 5 as an example. This test was also started with the initial relative density around 72% and after relative density reached 79% by applying pre-shear histories, the liquefaction test was conducted with the cyclic stress ratio of 1.0. However, since the generation of membrane wrinkles was significant after the first liquefaction stage, subsequent repeated liquefaction tests were not performed.

![Fig. 6. Effective stress path during liquefaction test.](image)

![Fig. 7. Stress-strain relationship during liquefaction test.](image)

3 TEST RESULTS AND DISCUSSIONS

3.1 Repeated liquefaction test without pre-shear history

As the references for comparison, a series of repeated liquefaction tests were conducted without pre-shear history. As an example, the effective stress path and the stress-strain relationship of the first liquefaction stage with the CSR of 1.0 are shown in Figure 6 and Figure 7, respectively. The liquefaction resistance curve indicated by the relationship between cyclic number to reach the maximum double amplitude of shear strain (denoted as liquefaction resistance) is shown in Figure 8. The relationship between relative density and cyclic number to reach the maximum double amplitude of shear strain ($\gamma(\gamma_{DA})_{max}$) of 7.5% and CSR is shown in Figure 8. The relationship between relative density and cyclic number to reach the maximum double amplitude of shear strain (denoted as liquefaction resistance) is shown in Figure 9. Based on the results shown in Figure 9, it can be concluded that the repeated liquefaction and reconsolidation histories resulted in the increase of relative density as well as the liquefaction resistance.

![Fig. 8. Liquefaction resistance curve of all liquefaction stages.](image)

![Fig. 9. Relationship between relative density and liquefaction resistance (without liquefaction history).](image)

3.2 Repeated liquefaction test with pre-shear histories

In order to investigate the influence of pre-shear history, all the liquefaction tests with pre-shear history were carried out with the same CSR of 1.0, and the details of all these cases are shown in Table 2. In this table, the resistance of liquefaction stages soon after pre-shear is indicated with $N_{c1}$ (cyclic number to reach $\gamma(\gamma_{DA})_{max}$ of 7.5%).

Figure 10 shows the relationship between relative density and liquefaction resistance of all liquefaction stages of all the cases listed in Table 2. Figure 11 shows the liquefaction resistance of the 1st stage of all cases with pre-shear histories along with that of all stages of cases without pre-shear history.
Table 2. Details of cases with pre-shear histories.

| Test ID | Details of pre-shear history | \( N_{c1}(\gamma_{DA_{\text{max}}} = 7.5\%) \) |
|---------|------------------------------|---------------------------------------------|
| B-1     | No pre-shear                 | 1.8                                         |
| B-6     | \( \gamma_{DA} = 0.2\% \times 100 \) cycles, drained | 2.2                                         |
| B-7     | \( \gamma_{DA} = 0.6\% \times 100 \) cycles, drained | 3.4                                         |
| B-8     | \( \gamma_{DA} = 0.6\% \times 200 \) cycles, drained | 15.3                                        |
| B-9     | \( \gamma_{DA_{\text{max}}} = 2\% \times 15 \) stages, undrained | 10.5                                        |
| B-10    | \( \Delta u_{\sigma_0} = 0.5 \times 18 \) stages, undrained | 88.7                                        |

Fig. 10. Relationship between relative density and liquefaction resistance (with liquefaction history).

Fig. 11. Liquefaction resistance of all cases.

The results of cases with pre-shear histories under drained condition showed that the liquefaction resistance of the 1st stage increased with the increase of strain amplitude as well as the cyclic number of pre-shears. However, the influence of pre-shears seemed to only work on the liquefaction stage soon after the pre-shear. In other words, it can be noticed that the strength of 2nd stages reduced to the similar value of the case without pre-shear history.

The result of Test B-9 showed a quite similar result with that of cases under drained condition. The strength of the 1st stage increased but soon dropped down from the 2nd stage of liquefaction.

As for Test B-10, the liquefaction test result showed a significantly increase in liquefaction resistance after this kind of incomplete liquefaction histories (excess pore water pressure generated but not enough to cause fully liquefaction). Further study needs to be done to check the behavior of subsequent liquefaction stages.

4 CONCLUSIONS

The following conclusions were obtained by conducting liquefaction tests with various kinds of pre-shear histories on dense sand specimens with the use of hollow cylindrical torsional shear apparatus.

1) Cyclic shear histories of \( \gamma_{DA} = 0.2 \) to 0.6\% under drained conditions increases the liquefaction resistance of the sand specimen. The degree of strength increase is affected by the shear strain amplitude and the cyclic numbers.

2) The small strain pre-shear history under drained conditions affects the liquefaction resistance only in the liquefaction stage immediately after that.

3) The pre-shear history under undrained conditions were found to increase the liquefaction resistance as well, but still only the liquefaction stage immediately after pre-shear was affected.

4) The liquefaction resistance increased significantly after the incomplete liquefaction histories.

Based on the results of this study, it is considered possible to reproduce sand specimens with high liquefaction resistance in the laboratory by utilizing the incomplete liquefaction history that most affects the liquefaction resistance. In the future, it will be necessary to conduct further detailed tests in order to investigate the mechanism by which pre-shear history affects liquefaction resistance.

ACKNOWLEDGEMENTS

This work was supported by JSPS KAKENHI Grant Number JP18H01531.

REFERENCES

1) Yoshimi, Y., Tokimatsu, K., Kaneko, O. and Makihara, Y. (1984): Undrained cyclic shear strength of a dense Niigata sand, *Soils and Foundations*, 24(4), 131-145.

2) Kiyota, T., Koseki, J., Sato, T. and Tsutsumi, Y. (2014): Effects of sample disturbance on small strain characteristics and liquefaction properties of Holocene and Pleistocene sandy soils, *Soils and Foundations*, 49(4), 509-523.

3) Ishihara, K. and Okada, S. (1978): Effects of stress history on cyclic behavior of sand, *Soils and Foundations*, 18(4), 31-45.

4) Goto, S. and Towhata, I. (2014): Acceleration of aging effect of drained cyclic pre-shearing and high temperature consolidation on liquefaction resistance of sandy soils, *Japanese Geotechnical Journal*, 9(4), 707-719 (in Japanese).