Effects of compaction thickness on liquefaction properties of two kinds of sandy soils prepared by moist-tamping method

Tomoko Sasaki i), Shima Kawamura ii) and Junichi Koseki iii)

i) Doctoral Student, Graduate School of Engineering, Muroran Institute of Technology, 27-1, Mizumoto-chou, Muroran Hokkaido 050-8585, Japan. ii) Associate Professor, ditto. iii) Professor, Department of Civil Engineering, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan.

ABSTRACT

In order to investigate the effects of preparation methods of specimens on liquefaction properties of two kinds of sandy soils, a series of cyclic undrained triaxial tests was performed on the sandy soils under the different conditions in grain size distribution and compaction thickness. Test specimens were prepared by the moist-tamping method. Test results showed that liquefaction resistances were influenced by the thickness of the compaction layer, and its tendency was changed depending on the grain size distribution and compaction degree, $D_c$. In addition, it was found that a difference in initial moisture content has an influence on deformation properties during cyclic loadings.

Keywords: liquefaction, specimen preparation, triaxial test, sandy soils

1 INTRODUCTION

It has been well known in laboratory element tests that liquefaction properties are affected by the difference in specimen preparation methods (Tatsuoka et al., 1986). Among various specimen preparation methods, the moist-tamping method has been often used in laboratory element tests, which has a high reproducibility because grain size distribution and water content can be widely selected.

In specimen preparation by moist-tamping method, test specimens are generally prepared by compacting soil samples layer by layer. As a result, it has been reported that the non-uniformity in the specimen is induced during the compaction process.

In this study, a series of cyclic undrained triaxial tests was performed on two kinds of sandy soils which are fine sand (Torryura sand) and well-graded sand to investigate the effects of the specimen-preparation methods on liquefaction resistance. In particular, the effects of the differences in grain size distribution and compaction thickness of the compacted specimens on liquefaction properties are discussed herein.

2 TEST MATERIALS

The test materials used in this study were Toyoura sand as fine sand and well-graded sand. The index properties, grain size distributions, and compaction curves of the materials are shown in Table 1, Figure 1, and Figure 2, respectively. As the characteristics of the soil materials, Toyoura sand is clean sand (poorly graded sand), and fines (less than 0.075mm) are hardly included. On the other hand, the coefficient of uniformity $U_c$ of well-graded sand is around ten times larger than that of Toyoura sand. In the compaction curves (see Figure 2), it can be pointed out that the peak of the curve for Toyoura sand is indistinct. This means that Toyoura sand is a soil material with a low compaction effect. In contrast, the peak of the curve is clearly confirmed for well-graded sand. It can also be said that this material is a soil material with a high compaction effect.

A series of cyclic undrained triaxial tests was conducted using two samples having different particle size distributions. In test cases of well-graded sands, the maximum soil particles were adjusted to within 4.75 mm for the specimen diameter of 75 mm. For Toyoura sand, although results from two batches are shown in Table 1, there was no significant difference between their liquefaction properties.

3 PREPARATION PROCEDURE OF SPECIMENS AND TEST METHOD

In this study, the specimens were 75 mm in diameter and 150 mm in height. The specimen preparation method in this study was the moist-tamping method (referred to as MT). Furthermore, the air-pluviation method (referred to as AP) was also adopted and the comparison of the mechanical behavior of Toyoura sand obtained from these two methods was made.
Table 2 shows the test conditions of specimens for each test. The number of compaction layers was either ten or four layers. The specimens of Toyoura sand or well-graded sand were compacted in the mold under the initial moisture content of 4% or 12.2% (the optimum moisture content) and 6.8% (natural moisture content), respectively (see Figure 2).

In the cyclic undrained triaxial test, all specimens were saturated using the double vacuum method. moisture content) and 6.8% (natural moisture content), respectively. In preliminary experiments, it has been confirmed that there is no effect on test results due to differences in the loading method and loading rate. Other test procedures were performed based on "Method for cyclic undrained triaxial test on soils" (JGS 0541-2009).

### 4 TEST RESULTS

#### 4.1 Liquefaction resistance

Figures 3 (a) and (b) show the time histories of effective stress path and stress-strain relationships for Toyoura sand and well-graded soil when the number of loading cycles $N_c$ at double amplitude axial strain $DA$ of 5% was around 20. In the comparison between Figure 3 (a) and Figure 3 (b), it is found that the effective mean principal stress $p'$ does not finally reach zero for well-graded sand although the decrease of $p'$ in the initial stage for well-graded sand is more significant than that of Toyoura sand.

Figures 4 (a) and (b) show the relationships between cyclic stress ratio CSR and the number of loading cycles $N_c$ required until $DA$ of 5% for Toyoura sand and well-graded sand, respectively. In the case of Toyoura sand, the CSR (at $N_c=20$) for specimens with ten layers was higher than that of specimens with four layers. The increase rate of CSR was around 9%. Also, the liquefaction curves, which are depicted in cyclic stress ratio versus $N_c$ were gentle for specimens with ten layers, whereas they were steep for specimens with four layers. In general, a similar mechanical behavior has been confirmed for specimens of loose-packed sands or specimens having a round shape of particles. The reason might be the effect of the interlocking of soil particles. In this test case, although the density of specimens and shapes of soil particles are the same, it has presumed that an interlocking effect between the particles due to the difference in the compaction layers is reflected.

Similarly, Figure 4(b) shows liquefaction resistance curves for well-graded soil. The degree of compaction $D_o$, which is dry density normalized to the maximum dry density, is 95%, 90%, and 85%. The initial moisture content corresponding to the optimum moisture content of $w_{opt}=12.2\%$ was adopted for preparation of specimens.
Effective mean principal stress $p'$ (kN/m$^2$)

Deviator stress $q$ (kN/m$^2$)

CSR = 0.274

Deviator stress

CSR (Nc=20) increases with an increase of $D_c$. On the other hand, the influence of compaction layers in the same conditions of $D_c$ on liquefaction resistances was smaller than that of Toyoura sand. In particular, the difference in liquefaction resistance was not clearly seen under the condition with lower value of $D_c$. In addition, the CSR (Nc=20) for specimens with four layers is slightly higher than those for specimens with ten layers, and its tendency was opposite to that of Toyoura sand. As a result, it can be inferred that liquefaction resistances are influenced by the thickness of the compaction layer, and its tendency was changed depending on the grain size distribution and compaction degree $D_c$, in other words, depending on the type of material.

4.2 Effect of compaction thickness on cyclic mechanical behavior of sandy soils

Figure 5 shows the relationship between the double amplitude axial strain normalized to $DA=5\%$ and $N_c$ required until $DA=5\%$ for Toyoura sand and well-graded sand. Figure 6 shows the relationship between the axial strain $\varepsilon_a$ and $N_c$ required until $DA=5\%$ for both types of sand. The above results were strongly affected by the number of loading cycles until $DA=5\%$. Therefore, the deformation behavior in the same $N_c$ before reaching $5\%$ of $DA$ is discussed herein.

As shown in Figures 5 (a) and 6 (a), it is found that the axial strain for Toyoura sand specimens with four layers is gradually developed compared with those for the specimens with ten layers. The results of the specimens prepared by the AP method show that the developments of axis strain were suddenly developed at around normalized $N_c=0.8$. From Figures 4(a), 5(a), and 6(a), it is apparent that the specimens prepared by the AP method behave like extremely loose specimens even if specimens are prepared under the same $D_c=95\%$, although the deformation behavior of $DA$ and $\varepsilon_a$ for specimens with ten layers prepared by the MT method has a similar tendency with that for specimens prepared by AP method. The above test results suggest that CSR ($N_c=20$) increases when the compaction thickness is thinner, and that deformation behavior is similar to those for loose specimens.

On the other hand, the developments of axial strain for specimens using well-graded soil were gentle when the degree of compaction $D_c$ increased (see Figure 5 (b) and Figure 6 (b)). In the comparisons of compaction thickness, the deformation behaviors for specimens with four layers are almost the same as those of specimens with ten layers for the case of lower condition of $D_c$. For $D_c=95\%$, although the development of axial strain for specimens with ten layers is slightly larger than that of specimens having four layers at the initial stage in loading, there is no difference in liquefaction strength for both cases.
Fig. 5. Relationship between double amplitude axial strain normalized to $DA=5\%$ and $N_c$ required until $DA=5\%$, $N_c/Ne$ at $DA=5\%$: (a) Toyoura sand, (b) well-graded sand.

Fig. 6. Relationship between axial strain and $N_c$ required until $DA=5\%$, $N_c/Ne$ at $DA=5\%$: (a) Toyoura sand, (b) well-graded sand.

Figure 7 shows the relationship between residual pore water pressure ratio and double amplitude axial strain normalized by $DA=5\%$ ($N_c=20$) for well-graded sand. In the case of the same moisture content, the residual pore water pressure was developed earlier than that of axis strain as the degree of compaction $D_c$ was lower. In general, this is similar to the trend obtained in other studies. In the comparison of compaction thickness, although the residual pore water pressure for specimens with four layers slightly increased earlier than those for specimens with ten layers. The effect of compaction thickness on liquefaction resistances was hardly confirmed for well-graded sand.

In order to elucidate the effect of compaction thickness on deformation behavior during consolidation, the relationships between the measured consolidation drainage volume ($\Delta V_{\text{measured}}$) and the calculated consolidation drainage volume ($\Delta V_{\text{calculated}}$) which was calculated by assuming an elastic body based on axial strain are shown in Figure 8. As can be seen from this figure, the drainage volume during consolidation for Toyoura sand is smaller than those for well graded sand. Furthermore, it is also apparent for well graded soil that the measured drainage volume is larger than the calculated volume. Although this reason has not been clarified, in any case, the discussions on micro structures are required.

Figure 9 shows the relationship between the drainage volume ratio ($\Delta V_{\text{calculated}} / \Delta V_{\text{measured}}$) and the degree of compaction, $D_c$. As shown in the figure, there is no difference in the drainage volume due to compaction thickness for $D_c=85\%$. However, specimens with four layers with $D_c=90\%$ and 95% indicate an isotropic consolidation behavior. Therefore, the effect of compaction thickness on deformation behavior during consolidation is significant and changed depending strongly on the difference in grain size distribution and compaction degree.

4.3 Effect of initial moisture content on the cyclic mechanical behavior of sandy soils

As mentioned in Figure 4 (b) for $D_c$ of 90%, the effect of the initial moisture content on liquefaction resistances was not significant. However, the developments of axial strain and residual pore water pressure before liquefaction are clearly different between specimens compacted under the initial moisture content of $w_i$ and the initial moisture content of $w_{opt}$.

According to Figures 5 through 7, it is found that the behavior of deformation and pore water pressure of specimens with $w=6.8\%$ and $D_c=90\%$ is similar to those with $w=12.2\%$ and $D_c=85\%$ rather than those with $w=12.2\%$ and $D_c=90\%$. It can also be said that the behavior of deformation and pore water pressure are like those for loose sands. In particular, specimens with an initial moisture content of 6.8% and $D_c=90\%$ indicate an isotropic consolidation behavior (see Figure 9). Therefore, the effect of variation of the orientation of soil particles due to compaction is not significant for specimens with $w=6.8\%$.

Figure 10 shows the relationships between the number of compaction (accumulation) and the depth of measurements from the upper surface of the specimen.
Fig. 7. Relationship between residual pore water pressure ratio and double amplitude axial strain normalized to $DA=5\%$ for well-graded sand.

Fig. 8. Relationships between measured drainage volume and calculated drainage volume during consolidation.

Fig. 9. Relationship between the drainage volume ratio and the degree of compaction.

Fig. 10. Relationship between number of compactions (accumulation) and the depth of measurements from upper surface of specimen for well-graded sand.

for $D_c$ of 90%. From the figure, it is apparent that the specimens under $w=6.8\%$ requires higher compaction energy than those under $w=12.2\%$ (the optimum moisture content).

In general, it has been said that soil structures in the specimen easily become random structures for a drier side on $w_{opt}$ in the compaction curve. In the case of the same compaction energy, the resistance between the particles becomes higher in the dry side on $w_{opt}$. As a result, dry density decreases as show it in Figure 2. The influence of the initial moisture content on soil structures and mechanical properties of compacted specimens has also been reported by several researchers (Miura and Toki, 1984, Kawajiri et al., 2011, Yokohama et al., 2014). As a result, liquefaction properties might be affected by the changes in soil structures during the compaction process.

5 CONCLUSIONS

In order to investigate the effects of the specimen preparation methods on liquefaction properties of two kinds of sandy soils, a series of cyclic undrained triaxial test was performed. The conclusions obtained are as follows;

1) Liquefaction resistance is influenced by the thickness of the compaction layer, and its tendency is changed depending on the grain size distribution and compaction degree, $D_c$.

2) In the comparison of two kinds of well-graded sands, the difference in initial moisture content has an influence on deformation properties during cyclic loading. In particular, the deformation behavior of the specimens compacted under lower moisture content is similar to those of loose sands.

REFERENCES

1) Kawajiri, S., Kawaguchi, T., Shibuya, S. and Takahashi, S. (2011): Effects of moulding water content and compaction method on deformation and strength characteristics of compacted soil, Journal of Japan Society of Civil Engineers, Ser. C(Geosphere Engineering), Vol.67, No.4, pp.532-543.(in Japanese)

2) Miura, S., and Toki, S. (1984): Anisotropy in mechanical properties and its simulation of sands sampled from natural deposits, SOILS AND FOUNDATIONS, Vol.24, No.4, pp.69-84.

3) Tatsuoka, F., Ochi, K., Fujii, S. and Okamoto, M. (1986): Cyclic undrain triaxial and torsional shear strength of sands for different sample preparation methods, SOILS AND FOUNDATIONS, Vol.26, No.3, pp.23-41.

4) Yokohama, S., Miura, S. and Matsumura, S. (2014): Change in the hydromechanical characteristics of embankment material due to compaction state conditions, SOILS AND FOUNDATIONS, Vol.54, No.4, pp.731-747.