LIQUEFACTION OF CLEAN SAND WITH STRATIFIED STRUCTURE DUE TO SEGREGATION OF PARTICLE SIZE

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ABSTRACT
This study focused on the effects of stratified structure due to segregation of particle size and graded bedding in clean sand deposits on their liquefaction characteristics. A well-graded clean sand was sieved and separated into four components with different ranges of particle size, and then deposited alternatively to create stratified structure in specimens. Undrained triaxial compression tests in monotonic loading conditions and cyclic triaxial loading tests were performed on these stratified samples as well as the uniformly mixed samples of the same sand. It was observed that the liquefaction resistance of the stratified specimens was larger than the uniform specimens. These test results indicate a possibility of underestimation of liquefaction resistance of deposits with laminar structure in situ, if it is evaluated in the laboratory using homogeneously reconstituted samples.

Key words: grain size distribution, liquefaction, sand, stratification, triaxial test, undrained shear strength (IGC: D6)

INTRODUCTION
Liquefaction strength of undisturbed samples is generally larger than the strength of remolded samples. This difference might be attributed to two kinds of soil structure different in scale, i.e. packing of particles in the scale of grain size, and laminar structure of the deposit in larger scale. Yoshimi et al. (1984, 1989) obtained undisturbed samples of a dense sand by means of in situ freezing and triple tube sampler from a site at Niigata, Japan. They conducted a series of undrained cyclic triaxial tests on the undisturbed samples as well as remolded samples, and reported a significant level of sample disturbance and remolding as shown in Fig. 1. This figure indicates that the liquefaction strength of the high quality undisturbed samples obtained by the in situ freezing technique was far larger than the strength of the “undisturbed” samples obtained by triple tube sampler that might suffer from some disturbances during the sampling process. These test results demonstrate the importance of microstructure of the sand such as particle arrangement and cementation between particles due to aging, which were fragile and affected by the small disturbances. Figure 1 also shows that the liquefaction strengths of reconstituted samples differed, depending on the method of remolding, and this fact confirms the importance of the effect of particle arrangement on the cyclic liquefaction of the sand. The coincidence of the test results from the undisturbed samples obtained by triple tube sampler and the samples reconstituted by air pluviation suggest that the air-pluviated specimens duplicated the microstructure of the “undisturbed” samples obtained by a triple tube sampler.

The effects of this kind of microstructure in the scale of the grain size should diminish if the material is largely deformed, because the bonding between particles should be destroyed and the packing of particles should be rearranged during the process of large deformation. Nevertheless, some researchers reported that the behaviors were different between undisturbed and remolded...

Fig. 1. Test result of undrained cyclic triaxial tests on a dense sand (after Yoshimi et al., 1984)
Castro et al. (1989), Seed et al. (1989), Marcuson et al. (1990) and Castro et al. (1992) executed a detailed exploration about the flow failure of Lower San Fernando Dam in 1971, including sampling of undisturbed soils from the hydraulic fill. The hydraulic fill soils contained high percentage of fine material as indicated by the gradation curve in Fig. 2, and the deposits were highly stratified with extensive layers on the order of 1 mm thickness (see photographs in Castro et al., 1989; Baziar and Dobry, 1995). The results of undrained triaxial compression tests on the silty soil from Lower San Fernando Dam were compiled and the steady state lines were plotted in Fig. 3. Apparently the undrained steady state strength of undisturbed samples were higher than that of remolded homogeneous samples. This discrepancy of steady state strength may be attributed to the graded and layered structure of the undisturbed samples that could be sustained at large deformation. In order to confirm this assumption, Baziar and Dobry (1995) conducted a series of tests on remolded specimens of the same soil that duplicated the original layered structure of grading by depositing the material through water to create graded bedding. These test results were also sited and plotted in Fig. 3. One may see that the steady state of the remolded but layered samples were positioned near to the steady state of undisturbed samples.

The layered and stratified structure due to gradation of particle size was schematically illustrated and shown in Fig. 4(a). The layered structure of undisturbed sample disappears if the soil is remolded and homogeneously reconstituted in laboratory. The remolded samples may have different packing of particles depending on the method of reconstitution, as illustrated in Figs. 4(b) and (c). Verdugo et al. (1995) made a distinction between the heterogeneous structures in larger scale and the arrangement of particles in the scale of the grain size by naming them as “structure” and “fabric”, respectively. With this terminology, the remolded sample shown in Fig. 4(b) duplicates the original anisotropic nature of “fabric”, but it does not reproduce the graded bedding “structure” of the undisturbed sample. Neither “structure” nor “fabric” is reproduced in the sample shown in Fig. 4(c).

The layered structure due to segregation of grain size is commonly observed both in natural and artificial soil deposits, especially if they were sediments through water, and the material is well graded. The layered structure could remain even after liquefaction and large deformation of the ground. Photo 1 shows a cross section of the ground at the left bank of Miyagawa River in Mobara city, Chiba prefecture, Japan. This ground moved towards the river with cracking and sand boiling during the Chiba-Toho-Oki Earthquake of 1987. The cracks in the surface soil and the sand dike shown in the photograph prove that the layered subsoil had completely liquefied. The layered structure in the liquefied deposit remained clear even though an extensive flow deformation occurred during the earthquake at this point.

On the other hand, layered structure due to segregation is difficult to be created if the soil is poorly graded. The Niigata sand obtained and tested by Yoshimi et al. (1984) had very narrow range of grain size distribution as shown in Fig. 2, thus it is suspected that the original soil in situ
was almost homogeneous without segregation. This may be the reason why the liquefaction strength of homogeneous samples reconstituted by air pluviation was almost the same as the strength of "undisturbed" samples obtained by triple-tube sampler. Also the cyclic liquefaction strength in the smaller strain levels could be affected by the layered structure if it existed.

Based on the background mentioned above, we created specimens of a clean sand with and without stratified structure due to segregation of the sand by grain size, and their liquefaction characteristics were compared both in monotonic and cyclic loading tests in this study.

MATERIAL USED, SAMPLE PREPARATION AND TEST PROCEDURE

JCA Sand with and without Stratification due to Segregation

The JCA sand is an industrial product of Japanese Cement Association (JCA) for the standard strength testing of cement. According to the standard of JCA, the original JCA sand has a particle size distribution with percentage passing of 100%, 93 ±5%, 67 ±5%, 33 ±5%, 23 ±5% and 1 ±1% by dry weight for the particle size of 2000 μm, 1600 μm, 1000 μm, 500 μm, 160 μm and 80 μm, respectively (Fig. 5). For the purpose of creating triaxial specimens with exactly the same entire particle size distribution for all of the tests, firstly we sieved the original sand and divided it into four parts with grain size range of 2000-850 μm, 850-425 μm, 425-250 μm and 250-75 μm. Then the divided materials were weighed and rearranged into a specimen to make the ratio of dry weight of 45.0%, 25.0%, 10.0% and 20.0% for each grade of particle size, respectively. Thus the arranged triaxial specimens had an unique particle size distribution with percentage passing of 100.0%, 55.0%, 30.0%, 20.0% and 0.0% by dry weight for the particle size of 2000 μm, 850 μm, 425 μm, 250 μm and 75 μm, respectively. This rearranged particle size distribution was almost the same as the original JCA sand as shown in Fig. 5. The density of the particle, maximum void ratio and minimum void ratio of the well-mixed homogeneous JCA sand measured by the standard methods of Japanese Geotechnical Society (JGS) are \( \rho = 2.644 \text{ g/cm}^3 \), \( e_{\text{max}} = 0.729 \) and \( e_{\text{min}} = 0.463 \), respectively.

The triaxial samples had diameter of about 50 mm and height of about 100 mm. Although the water sedimentation method may create particle packing more similar to natural deposits, the air-pluviation method was adopted in this study in order to create clearly segregated or uniform specimen in contrast. All specimens of JCA sand were deposited in five layers. In the case of creating segregated and stratified specimens, each layer was deposited in four sub-layers with different range of particle size, thus a specimen consisted of 20 sub-layers in total. Firstly the component of oven-dried JCA sand with the largest grain size (range of 2000-850 μm) was weighed and pluviation into a mold from a nozzle with circular opening of 7 mm in diameter. Next, the sand with grain size range of 850-425 μm, and then the component with grain size of 425-250 μm were pluviation from a slit with an opening of 1 mm in width and 10 mm in length. Finally the finest sand component with grain size of 250-75 μm was pluviation from a slit with width of 1 mm and length of 6 mm, and a graded unit layer was created. The same procedure was repeated five times and then a stratified specimen was completed. The density of the specimens were adjusted by changing the height of pluviation from 0 cm to 60 cm, but the height was kept constant during composition of each individual specimen.

Also in the case of creating homogeneous and uniform JCA sand specimens, the sand was deposited in five layers to minimize segregation. The sieved and segregated components of the dry sand for one layer were weighed and mixed thoroughly together, and pluviation through the nozzle with a circular opening of 7 mm in diameter. This was repeated five times to complete a specimen. Photo 2 shows the triaxial specimens of uniform and stratified JCA sand. These different packings of JCA sand are schematically illustrated in Fig. 6.
Toyoura Sand with and without Stratification of Dense-Loose Layers

In addition to JCA sand, Toyoura sand that has particle density of $\rho_s = 2.650 \text{ g/cm}^3$, maximum and minimum void ratios of $e_{\text{max}} = 0.977$ and $e_{\text{min}} = 0.597$, respectively, was utilized for the examination purpose of the effect of uniformity of density-distribution in a specimen. The slit with width of 1 mm and length of 10 mm was used for air-pluviation of Toyoura sand. When specimens of Toyoura sand with stratification in density were constituted, the sand was deposited in five layers and each layer consisted of a dense sub-layer and a loose sub-layer (10 sub-layers in total in a specimen). The dense sub-layer was pluviated from a height of 30 cm that resulted in a relative density of about $D_r = 72\%$, whereas the loose sub-layer was deposited with zero height that resulted in about $D_r = 15\%$. The uniform specimens of Toyoura sand were pluviated without layer divisions, because the particle size range of Toyoura sand is very narrow as shown in Fig. 5, and thus segregation is impossible.

TEST RESULTS

Undrained Triaxial Compression Tests on JCA Sand

Nine triaxial compression tests were performed on JCA sand in undrained and monotonic loading conditions, as listed in Table 1. Four uniformly deposited specimens (Test No. 01–04) and five stratified specimens with graded bedding structure (Test No. 05–09) were sheared in this test series. The deviator stress—axial strain curves and stress path on deviator stress—effective mean stress plane for the uniform and stratified specimens were plotted in Figs. 7 and 8, respectively. If these figures are compared, one may notice a big difference in the shear behaviors of the uniform and stratified JCA sand. The stratified specimens behaved far stiffer and more dilative than the uniform specimens, although the material and its composition were completely the same in these two kinds of specimen.

For the purpose of direct comparison of these test results, the phase transformation lines and the steady state lines are shown in Fig. 9. The phase transformation (PT) is defined as the state at the minimum effective mean stress.
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(a) principal stress ($p_{\text{in}}$) during the undrained shear process, and the steady state (SS) is the state of constant effective stress components attained at large deformation. The phase transformation line represents the minimum undrained strength, and generally converged into the steady state line when the void ratio becomes larger and converged into the vertical line at the initial effective confining stress (the initial state line) when the void ratio becomes smaller in the $e-p'$ plot (Yoshimine and Ishihara, 1998). The lower part of the steady state line for the stratified deposit of JCA sand in Fig. 9 (the broken line) is only estimated and its exact position is unknown, because the tests of stratified specimens except the loosest one were terminated before attaining the real steady state due to the limitation of the apparatus as shown in Fig. 8. Nevertheless, Fig. 9 clearly indicates that the positions of the phase transformation line and the steady state line of stratified deposit are much higher than those of uniform deposit. The effective stress and the undrained shear resistance of stratified deposit could be larger than those of the uniform deposit by ten times or more, especially when the density of the sand is smaller.

Undrained Cyclic Triaxial Tests on JCA Sand

Thirteen undrained triaxial cyclic loading tests were performed on JCA sand as listed in Table 2. Seven uniformly deposited specimens (Test No. 10–16) and six graded and stratified specimens (Test No. 17–22) were

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**Table 1. Triaxial compression tests on JCA sand ($p_0 = 100$ kPa)**

<table>
<thead>
<tr>
<th>Test no.</th>
<th>Structure</th>
<th>Void ratio $e$</th>
<th>Relative density $D_r$ (%)</th>
<th>Modified relative density $D_{mr}$ (%)</th>
<th>Effective stress at PT $p_1$ (kPa)</th>
<th>Effective stress at the end of test $p_2$ (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>Uniform</td>
<td>0.628</td>
<td>38.0</td>
<td></td>
<td>61.8</td>
<td>107.1</td>
</tr>
<tr>
<td>02</td>
<td>Uniform</td>
<td>0.577</td>
<td>57.1</td>
<td></td>
<td>86.2</td>
<td>335.3</td>
</tr>
<tr>
<td>03</td>
<td>Uniform</td>
<td>0.548</td>
<td>68.0</td>
<td></td>
<td>86.8</td>
<td>352.8</td>
</tr>
<tr>
<td>04</td>
<td>Uniform</td>
<td>0.485</td>
<td>91.7</td>
<td></td>
<td>85.8</td>
<td>885.6</td>
</tr>
<tr>
<td>05</td>
<td>Stratified</td>
<td>0.734</td>
<td>-1.9</td>
<td>51.1</td>
<td>86.2</td>
<td>816.3</td>
</tr>
<tr>
<td>06</td>
<td>Stratified</td>
<td>0.699</td>
<td>11.3</td>
<td>64.1</td>
<td>94.3</td>
<td>826.8</td>
</tr>
<tr>
<td>07</td>
<td>Stratified</td>
<td>0.689</td>
<td>15.0</td>
<td>67.8</td>
<td>99.7</td>
<td>844.7</td>
</tr>
<tr>
<td>08</td>
<td>Stratified</td>
<td>0.624</td>
<td>39.5</td>
<td>91.9</td>
<td>99.8</td>
<td>977.5</td>
</tr>
<tr>
<td>09</td>
<td>Stratified</td>
<td>0.557</td>
<td>64.7</td>
<td>116.7</td>
<td>100.2</td>
<td>1022.5</td>
</tr>
</tbody>
</table>
tested in this series. Figures 10, 11 and 12 are the examples of the test results with cyclic stress ratio of \( \frac{\tau_y}{\sigma'} = 0.2 \). In these figures, the cyclic shear stress \( \tau_y \), axial strain \( \varepsilon \), and excess pore water pressure \( u_e \) are plotted versus the number of cycles. Figure 10 is the result of Test No. 22 with stratified specimen that had void ratio of \( e = 0.564 \) and relative density of \( D_r = 62\% \). This specimen hardly liquefied, and nearly 1000 cycles were needed to attain liquefaction. On the other hand, it was found that the liquefaction resistance of uniform samples was considerably lower. Figure 11 is the result of Test No. 11 using uniform deposit with void ratio of \( e = 0.567 \) and relative density of \( D_r = 61\% \). This specimen liquefied only in 2 cycles although it had almost the same density as the stratified specimen No. 22 shown in Fig. 10. The result of the dense uniform specimen No. 15 that had void ratio of \( e = 0.451 \) and relative density of \( D_r = 105\% \) is displayed in Fig. 12. Although this uniform specimen No. 15 (Fig. 12) was much denser, it liquefied in much smaller number of cycles compared with the stratified specimen No. 22 (Fig. 10).

All the cyclic tests on JCA sand were summarized in Figs. 13 and 14 by plotting the cyclic stress ratio versus the number of cycles causing liquefaction of each test.

The number of cycles causing liquefaction \( (N) \) was defined by the development of double amplitude of axial strain up to 5\%. Comparison of Figs. 13 and 14 confirms the large influence of layered structure of sand on its liquefaction strength characteristics. If liquefaction strength is defined by the cyclic stress ratio for \( N = 10 \), the strength of stratified JCA sand with relative density of \( D_r = 50\sim60\% \) could be 1.5 to 2 times larger than the...
The discrepancy of undrained responses between layered and homogeneous specimens, both in monotonic and cyclic loading, might be affected by the thickness of one unit layer in the layered specimen. If the thickness of layers becomes very small, the nature of the whole specimen becomes close to the homogeneous one, and the responses should be similar to each other.

Effects of Non-homogeneity in Density

There is some possibility that the difference of the densities in different sub-layers of different grain size grading could affect the test results presented in the previous sections, although the layered specimens of JCA sand were prepared by air pluviation from the same height during the deposition process of all layers and segregated sub-layers in an individual specimen. To examine this aspect of non-uniformity of density in a specimen, we conducted a series of undrained triaxial compression tests on stratified specimens that consisted of alternate dense-loose layers with strong contrast in density, and compared the behavior with uniformly
deposited specimens. Toyoura sand that has very narrow range of grain size distribution was used in this test series to avoid the effects of segregation of particles. The test conditions and main results are listed in Table 3, and stress-strain curves and stress path of selected tests are plotted in Fig. 15. It seems that the undrained behavior of dense-loose stratified specimens was somewhat softer than uniform specimens, but the difference is not so large. Figure 16 is the plot of the state of phase transformation in this test series of Toyoura sand. The phase transformation line for dense-loose stratified deposit is located lower than that of uniform deposit while the difference in the position is small. We can even say that the difference may be negligible if we recall the extremely big contrast in densities in the layers of stratified specimen. Furthermore, the effect of stratification in density (softer if stratified) is the opposite of the effect of stratified structure due to segregation (stiffer if stratified). Therefore we can conclude that the test results on the stratified JCA sand specimens such as that shown in Figs. 9 and 14 were hardly affected by non-uniformity of the density in the specimens.

EVALUATION OF THE TEST RESULTS BY MEANS OF MODIFIED RELATIVE DENSITY

Although the behavior of segregated and stratified JCA sand was compared with uniformly deposited sand through void ratio or relative density in the previous sections, it is somewhat doubtful if these indexes of density are appropriate or not for the comparison purposes. Relative density is always calculated from the maximum and minimum void ratios of completely mixed material. However, segregated layers are essentially poorly graded even though the entire deposit has well-graded particle size distribution, and thus graded and stratified deposit might have larger potential of creating looser packing of grains. In other words, the “real” maximum and minimum densities of graded and stratified deposit could be smaller than those of uniformly mixed deposit, and this could result in underestimation of the relative density of deposits with graded bedding structure. For example, if in situ penetration resistances such as N-value in SPT and $q_c$-value in CPT are the same level in two soil deposits with and without stratified structure of segregation, the density of the stratified deposit must be smaller than the density of the uniform deposit. Therefore the undrained strength characteristics of these two deposits may not be so different if compared with the indexes measured by the in situ testing.

Taking into account of the above considerations, we will introduce modified relative density ($D_{rn}$) for graded and stratified sand in order to evaluate their behavior more accurately. If a soil sample consists of $n$ components or layers segregated, the modified maximum and minimum void ratios of the entire sample are calculated by:

$$e_{\text{max}} = \sum_{i=1}^{n} \left[ R_{m,i}(e_{\text{max},i} + 1) \right] - 1$$

(1)

$$e_{\text{min}} = \sum_{j=1}^{n} \left[ R_{m,j}(e_{\text{min},j} + 1) \right] - 1$$

(2)

where $e_{\text{max},i}$ and $e_{\text{min},j}$ are the maximum and minimum void ratios of the $i$th segregated component, and $R_{m,j}$ is the ratio of the dry weight of the $i$th component to the total dry weight of the entire sample. Thus the modified relative density of the sample is obtained by:

$$D_{rn} = \frac{e_{\text{max}} - e}{e_{\text{max}} - e_{\text{min}}} \times 100[\%]$$

(3)

where $e$ is the void ratio of the entire sample.

The four components of sieved and separated JCA sand were tested and the maximum and minimum void ratios of each individual segregated component were measured by JGS standard method, as listed in Table 4.

### Table 4. Maximum and minimum void ratios of segregated and uniform JCA sand

<table>
<thead>
<tr>
<th>Range of grain size</th>
<th>Dry weight ratio</th>
<th>Min. void ratio</th>
<th>Max. void ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D(\mu m)$</td>
<td>$R_m$</td>
<td>$e_{\text{min}}$</td>
<td>$e_{\text{max}}$</td>
</tr>
<tr>
<td>Uniformly mixed JCA sand</td>
<td>75–2000</td>
<td>1.000</td>
<td>0.463</td>
</tr>
<tr>
<td>Sieved and segregated JCA sand</td>
<td>75–250</td>
<td>0.200</td>
<td>0.544</td>
</tr>
<tr>
<td></td>
<td>250–425</td>
<td>0.100</td>
<td>0.564</td>
</tr>
<tr>
<td></td>
<td>425–850</td>
<td>0.250</td>
<td>0.597</td>
</tr>
<tr>
<td></td>
<td>850–2000</td>
<td>0.450</td>
<td>0.638</td>
</tr>
<tr>
<td>Stratified sample of JCA sand</td>
<td>Overall</td>
<td>0.602</td>
<td>0.872</td>
</tr>
</tbody>
</table>
The modified maximum and minimum void ratios calculated by Eqs. (1) and (2) were $e_{\text{max}} = 0.872$ and $e_{\text{min}} = 0.602$, respectively, for the stratified JCA sand specimens used in this study. These maximum and minimum void ratios for the stratified JCA sand are much higher than those of uniformly mixed JCA sand, whereas the void ratio ranges ($e_{\text{max}} - e_{\text{min}}$) are almost the same. The modified relative densities of the stratified specimens of JCA sand tested in this study were calculated by Eq. (3) and listed in Tables 1 and 2.

The results of undrained triaxial tests on JCA sand presented in the previous sections will be re-evaluated taking advantage of the newly proposed modified relative density. Figure 17 shows the behaviors of stratified JCA sand and uniform JCA sand in the undrained monotonic loading tests compared through the modified relative density. One may notice that the discrepancy of the undrained behaviors due to grading and stratified structure is much smaller than in the case of using the normal relative density (Fig. 9). Nevertheless, the stratified specimens behaved stiffer than uniform specimens even though compared through the modified relative density, especially at larger deformation and if the density was not so high. The results of cyclic loading tests are summarized and plotted in Fig. 18. In the same manner as the monotonic loading tests, although the difference of cyclic liquefaction strengths between stratified and uniform specimens became smaller when compared with the evaluation by normal relative density plotted in Figs. 13 and 14, it can be said that stratified deposit had larger liquefaction strength than uniformly deposited material which had the same modified relative density.

We assumed perfect segregation of the layers in the calculation of the modified relative density using Eqs. (1) to (3), whereas, in reality, some mixture should exist at the boundaries of layers in the tested specimens. Therefore the “real” modified relative densities of the layered specimens should be smaller than that calculated, and the differences in liquefaction resistances between layered and homogeneous specimens should be greater than what Figs. 17 and 18 depicted.

Note again that the relative density is commonly and normally calculated based on the maximum and minimum void ratios of the completely mixed and uniform material, and it may be very difficult to evaluate the modified relative density of the graded deposits ($e_{\text{max},i}$, $e_{\text{min},i}$, and $R_{\text{mi}}$ values of the segregated components) in practical works. In addition, the analysis based on the relative densities is impossible if the material has larger fines contents because of the limitation of the index test. Although only clean sand was examined in this study, sandy soils with fines may have higher potential of segregation and creating stratified structure in natural deposits. The investigation of the effects of layered structure in the deposit of silty sand is in process by authors, and will be reported in future.

CONCLUSIONS

Effects of stratified structure due to segregation of particle size in clean sand deposits on their liquefaction characteristics were examined in this study. A well-graded sand but without fines and gravel contents was sieved and separated into four components with different ranges of particle size, and then deposited alternatively to create stratified structure in specimens. Undrained triaxial compression tests in monotonic loading conditions and cyclic triaxial loading conditions were performed on these stratified samples as well as the uniformly mixed samples of the same sand. The following are the main conclusions derived from the test results.

1. Liquefaction resistances of sand, both in monotonic and cyclic triaxial tests were considerably affected by the stratified structure due to segregation. The stratified sand was much more dilative and stiffer compared to the uniform sand of the same density. This fact indicates that the in situ liquefaction resistance of natural deposits with graded bedding could be highly underestimated by triaxial testing if remolded and uniformly reconstituted specimens were used in the laboratory.

2. The maximum and minimum void ratios of segregated and stratified sand were much larger than those of uniformly deposited sand. Although the maximum and minimum densities are usually
measured by the index tests on remolded and uniformly mixed samples in laboratory, using these indexes results in large underestimation of the real relative density of the undisturbed samples or the sand in situ, if the original deposit has stratified structure in the ground.

3. The test results were re-evaluated by modifying the relative densities of the stratified specimens based on the real maximum and minimum void ratios of the segregated and stratified deposit. It was found that the undrained resistance of stratified sand was still larger than the uniformly mixed sand even though it was compared through the modified relative density. This discrepancy in undrained behavior may be attributed to the pure effect of the difference in gradation of soil particles. Segregated sand is essentially poorly graded even if the whole deposit is well graded with wide range of particle size distribution. Well graded mixture of soils may be contractive not only in compaction by vibration but also in dilatancy characteristics during shearing, whereas the segregated and stratified deposit of the same soil could be more dilative. This intrinsic difference of gradation of soil should cause different undrained behaviors in any mode of shear such as simple shear condition, although only triaxial tests were conducted in this study.

4. The effect of stratification in density of sand on its undrained behavior was also examined by testing dense-loose layered specimens. The effect was smaller and the opposite of the effect of stratified structure due to segregation. The dense-loose stratified specimens were slightly more contractive than the uniform specimens in undrained triaxial compression tests.

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