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RELIQUEFACTION POTENTIAL OF CEMENT-TREATED SANDY SOILS

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SUMMARY

It is known that the cement-treated method is useful in preventing the liquefaction of saturated sandy soil deposits. However, it is not known whether the reliquefaction strength of cement-treated sandy soil deposits which liquefied due to a large earthquake is greater or lesser than the original liquefaction strength. In the present investigation, a series of shaking table tests were performed in order to evaluate the reliquefaction strengths of two kinds of cement-treated sandy soils. Furthermore, observations of the soil particle structure of the cement-treated soils, both before and after the first liquefaction, were carried out using a scanning electron microscope (SEM)

INTRODUCTION

There have been numerous studies on methods of preventing liquefaction by adding small amounts of cement to sandy soil, and such methods have proven effective in practice. However, no studies have yet clarified the liquefaction resistance of such treated soil after liquefaction caused by the main shocks of a large earthquake; its resistance to aftershocks or subsequent earthquakes remains unknown. In the 1995 Hyogoken-Nambu earthquake, since structures thought to be earthquake-resistant were damaged, it is important to predict the reliquefaction resistance of cement-treated soils already exposed to liquefaction. To do so, we carried out shaking table tests on cement-treated samples in a Kerman-type simple shear box fixed onto a shaking table, and studied their liquefaction and reliquefaction potentials. This paper presents the experimental procedure and results obtained.

SOIL SAMPLES AND STABILIZER

The soil samples used in this study were Toyoura standard sand (hereafter "Toyoura sand") and masado sampled from the surface layer of granite region in Ube City (hereafter "masado"). Table 1 and Figure 1 list the physical properties and grading curves of the two samples, respectively. Slag cement B was used as the stabilizer, and strongly anionic polyacrylamide as the bonding agent.

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Table 1: Physical properties of the soil samples

		Toyoura sand	Ube masado
Specific gravity	G_s	2.655	2.624
Maximum grain size	D_{max} (mm)	0.850	4.750
Average grain size	D_{50} (mm)	0.185	0.840
Uniformity coefficient	U_c	1.82	16.62
Maximum void ratio	e_{max}	0.929	0.902
Minimum void ratio	e_{min}	0.619	0.569
Fines content	F_c (%)	0.2	11.2

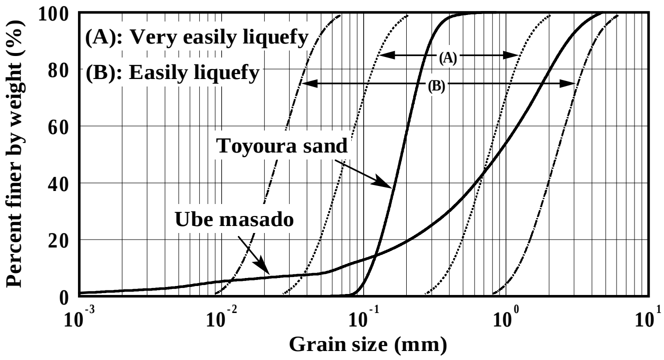


Figure 1: Grading curves of the soil samples

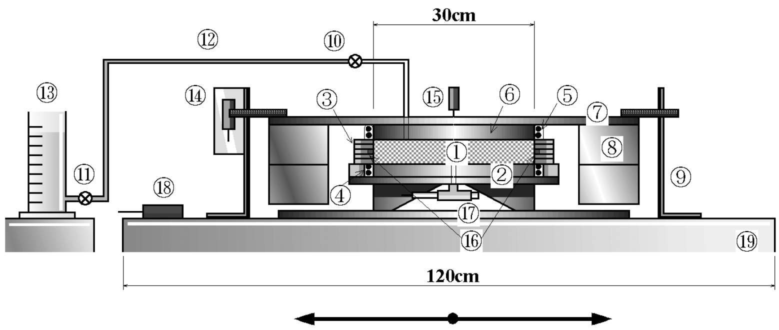
3. EXPERIMENTAL APPARATUS

Figure 2 shows a schematic diagram of the Kerman-type simple shear box used in this study. A detailed description of the box follows. The shear box consists of five doughnut-shaped PVC rings placed around a 1-mm thick rubber membrane. The four lower rings are 1.0-cm thick, with inner and outer diameters of 30.0 cm and 35.0 cm, respectively. The uppermost ring has the same thickness and outer diameter, but its inner diameter is enlarged to 30.2 cm, so that the loading plates can be placed securely onto the specimen. A small pressure transducer is attached to the third ring to measure the horizontal stress produced in the sample while the box is in motion. The stress was analyzed at 4 points: 2 points parallel to and 2 points perpendicular to the direction of shaking.

Vertical stress was applied to the sample surface by doughnut-shaped lead weights, and shear stress was applied by the inertial force of the weights during the shaking. In the present study, all initial effective vertical pressure σ'_{v0} was 49 kPa.

4. EXPERIMENTAL PROCEDURE

The samples were prepared in the following method. Stabilizer equal to 5 wt.% of the dry soil sample was added to the sample and mixed thoroughly to created an uniform mixture. Then a bonding agent solution (concentration 100 mg/kg) was stirred into the mixture while removing air from the mixture. Then the mixture was slowly poured into the shear box. The sample mixture was poured into three layers. After pouring each layer, the surface was smoothened by pressing with a wooden tamper. Then, vertical pressure σ'_{v0} was applied to the sample surface, and the sample was let to cure at a drained state. The curing time was set to 1, 3, and 14 days to observe the reliquefaction potentials for different solidification conditions at constant amounts of additives.



Direction perpendicular to shaking direction

① Specimen	**② Shear box**
③ Polyvinyl chloride rings	**④ O-rings**
⑤ Rubber membrane	**⑥⑦ Loading plates**
⑧ Lead weights	**⑨ Stoppers**
⑩⑪ Valves	**⑫ Rigid pipe**
⑬ Measurement cylinder	**⑭⑮ Displacement transducer**
⑯ Pressure transducer	**⑰ Pore water pressure transducer**
⑱ Accelerometer	**⑲ Shaking table**

Figure 2: Experimental apparatus

After each curing time, the shaking table was moved at a frequency of 1/3 sec., with constant amplitude and sinusoidal acceleration.

The reliquefaction experiment was carried out following the initial liquefaction test. Once liquefaction occurs, the soil particles that were solidified by cement become disaggregated, and soil particles flowed into the space between the rubber membrane and the loading plates, and the upper portion of the sample expands. Therefore, after the initial liquefaction, the valves were opened to release the pore water pressure. Then, the expanded portion was removed according to the method of Yamamoto et al. (1997). After that, the vertical pressure was again applied to the sample, and the shaking table was moved to carry out the reliquefaction test.

For comparison, we also carried out tests using samples without stabilizers (untreated samples). The horizontal accelerations applied to the sample were approximately the same for the initial liquefaction and the reliquefaction tests in Yamamoto et al. (1997). However, in this test on the treated samples, the horizontal acceleration of the initial liquefaction test was significantly larger than that for the reliquefaction test.

5. RESUITS AND DISCUSSIONS

5.1 Reliquefaction potential

Figures 3(a) and (b) show liquefaction resistance curves obtained for Toyoura sand and masado in the initial liquefaction and the reliquefaction tests. The horizontal axis represents the number of cycles (n_L) required to cause liquefaction, and the horizontal axis represents the stress ratio (τ/σ'_{v0}) on the sample bottom. The symbol ∞ means that liquefaction did not occur. Liquefaction was defined as the state when the double-amplitude shearing strain γ reaches 10%.

From Figures 3 (a) and (b), it can be seen that adding cement to both treated soils significantly increases the initial liquefaction resistance compared to that of untreated soils. Furthermore, the longer the curing period, the stronger the liquefaction resistance. We carried out the same test on Toyoura sand sample cured for 28 days and observed no initial liquefaction. The reliquefaction resistances of all treated samples are lower than the initial liquefaction resistances. When we compare the stress ratios of each sample at n_L=20, it can be seen that the reliquefaction resistances of samples cured for 3 and 14 days are nearly half of the initial liquefaction

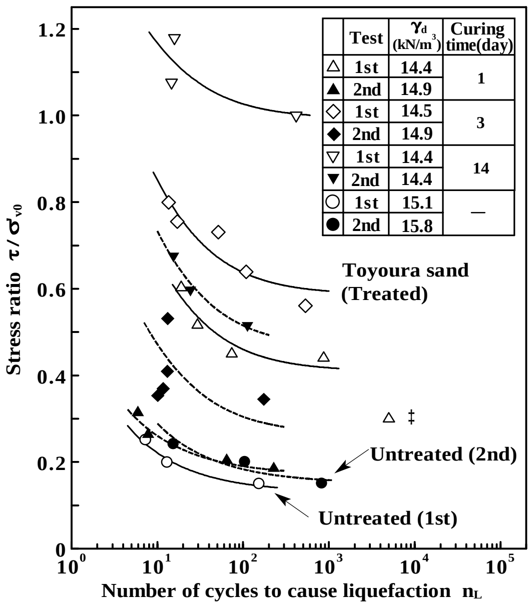


Figure 3(a): Liquefaction resistance curves for Toyoura sand

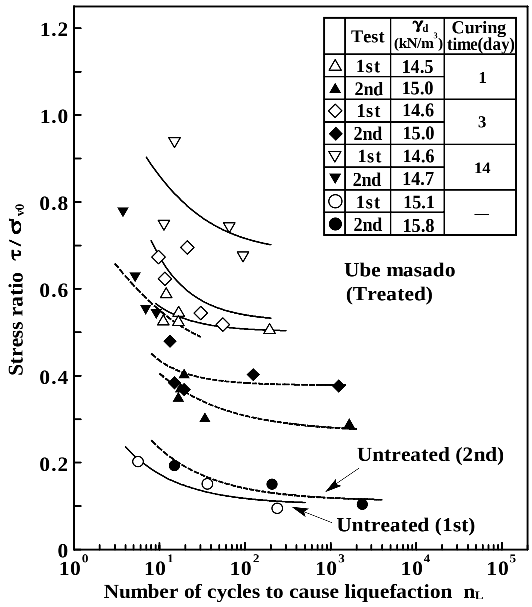


Figure 3(b): Liquefaction resistance curves for masado

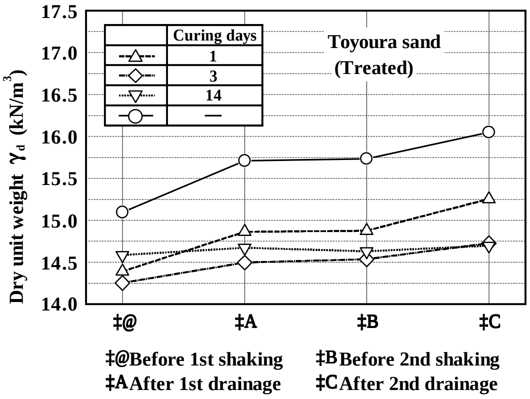


Figure 4(a): Changes in densities at various steps in the tests for Toyoura sand

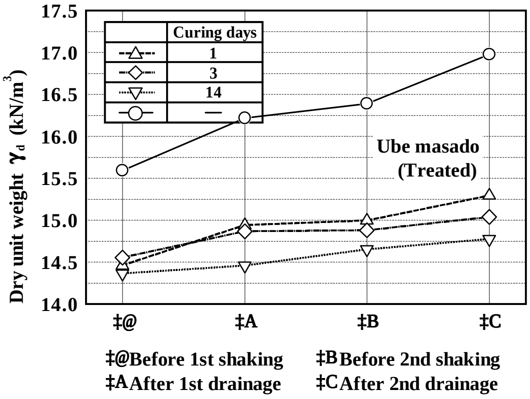


Figure 4(b): Changes in densities at various steps in the tests for masado

resistances. The reliquefaction resistance of the Toyoura sand sample cured for 1 day is almost as low as that for the untreated soil. We believe that the initial liquefaction may have broken the bond between the cemented soil particles. As a result, structurally unstable and weak portions were created in the samples, which lowered the reliquefaction resistance. The reliquefaction resistance of untreated soils (●) are larger than the initial liquefaction resistance (○). This may be a result of density increase caused by compaction due to drainage after the initial liquefaction. Furthermore, it can be seen from Figure 3 (b) that there is some dispersion in the reliquefaction resistance of masado samples cured for 14 days. This results from the difference in the destruction mechanism of the samples. This will be discussed in more detail in a later section.

Figures 4 (a) and (b) show the changes in the dry density γ_d during the test processes for Toyoura sand and masado, respectively. Samples with shorter curing times show larger increases in density for both the initial liquefaction and reliquefaction tests. The sample cured for 14 days shows a small decrease in density. From these results, we conclude that samples with shorter curing times have weaker degrees of bonding between the soil particles, and therefore their bonds are easily broken by liquefaction and reliquefaction, and they show a significant density increase due to compaction.

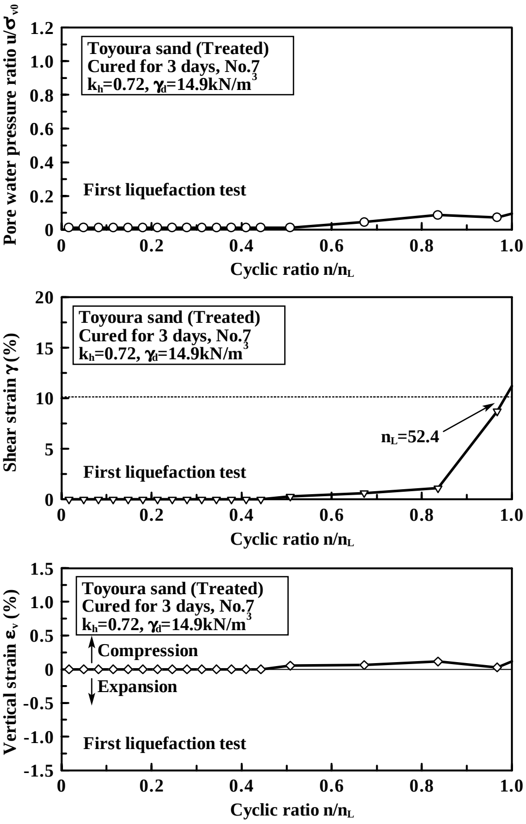


Figure 5(a): Changes in pore water pressure u/σ'_{v0}, shearing strain γ, and vertical strain ε_v for Toyoura sand sample cured for 3 days in the initial liquefaction test

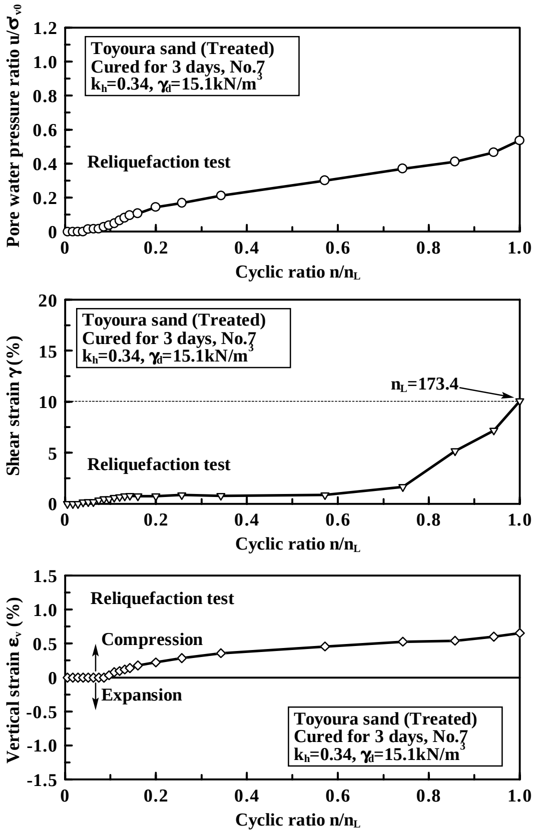


Figure 5(b): Changes in pore water pressure u/σ'_{v0}, shearing strain γ, and vertical strain ε_v for Toyoura sand sample cured for 3 days in the reliquefaction test

Figures 5 (a) and (b) show representative variations in pore water pressure ratio u/σ'_{v0}, shearing strain γ, and vertical strain ε_v during the initial liquefaction and reliquefaction tests for Toyoura sand sample. These are the results of Toyoura sand samples cured for 3 days. Readers are referred to Yamamoto et al. (1998a) and Yamamoto et al. (1998b) for test results of untreated samples and samples cured for 1 day. The horizontal axis represents cyclic ratio ($=n/n_L$), with the ratio of 1 representing the time when the shearing strain γ in the sample reached 10%. It can be seen that the maximum increase in pore water pressure is about 80% in both liquefaction and reliquefaction tests.

When the shearing strains of the initial and the reliquefaction tests are compared, it can be seen that in the initial liquefaction, the shearing strain increases rapidly after a certain number of cycles and attains liquefaction, while in the reliquefaction test, the shearing strain increases gradually and attains liquefaction.

Figures 6 (a) and (b) are histories of masado samples cured for 14 days. From Figures 5 and 6, it can be seen that the pore pressure ratio of masado sample cured for 14 days is nearly the same as that of the Toyoura sand sample cured for 3 days. Also, the masado samples show almost no vertical strain before $n/n_L<1$, and show a steep increase at $n/n_L=1$. These trends in the shearing strain and vertical strain for masado samples cured for 14 days is also observed for those of the Toyoura sand samples cured for 14 days. Especially, the vertical strain of the Toyoura sand sample cured for 14 days showed a temporary increase after the cyclic ratio reached 1.

Photograph 1 shows a sample after the reliquefaction test. This sample was masado cured for 14 days. An arrow in the photograph indicates a nearly horizontal failure surface formed in the sample. The lower portion of the masado sample shows evidence of liquefaction even though cement was added to the sample, and the structure of the soil particles were heavily disrupted. All other portions were intact. The dispersion in the reliquefaction resistance of the masado samples cured for 14 days as seen in Figure 3 (b) is thought to result from the separation of the sample into a liquid and a solid portion through liquefaction.

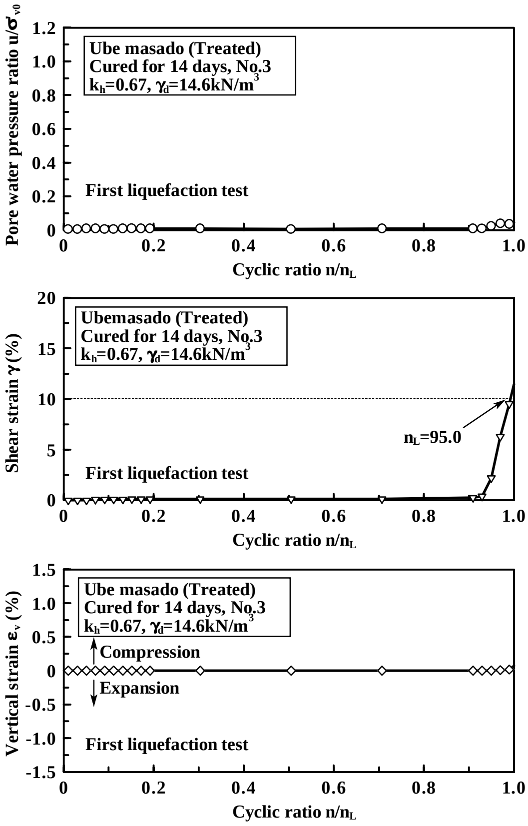


Figure 6(a): Changes in pore water pressure u/σ'_{v0}, shearing strain γ, and vertical strain ε_v for masado sample cured for 14 days in the initial liquefaction test

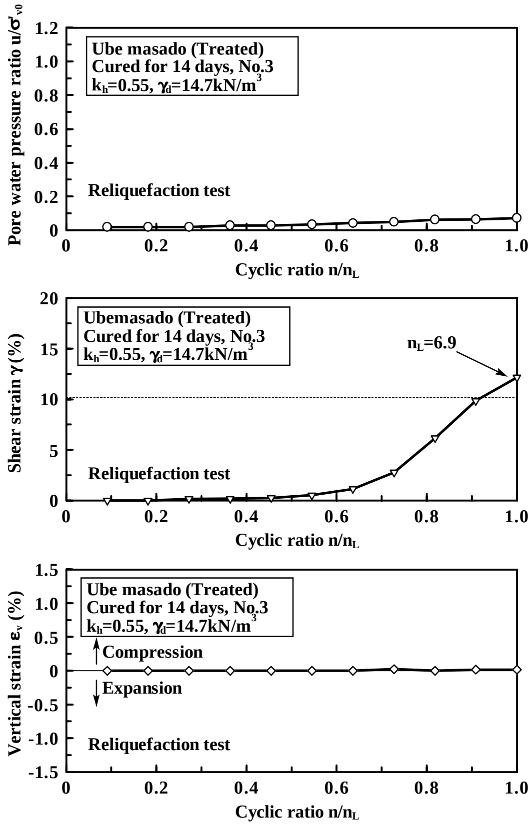


Figure 6(b): Changes in pore water pressure u/σ'_{v0}, shearing strain γ, and vertical strain ε_v for masado sample cured for 14 days in the reliquefaction test

From the above discussions, the density of samples cured for 3 days increases because soil particles become disaggregated and are redeposited. This is a similar trend seen in resedimentation of sand layers following actual liquefaction. It can be said that 3 days is not enough for solidification of soil particles. On the other hand, the degree of solidification seen in masado samples cured for 14 days is significantly large, and the sample has an apparently dense structure, and is nearly rigid. Therefore, destruction of such samples shows a different mechanism than liquefaction, and occurs in a localized area. With the plane of failure as the boundary, the upper portion of the sample overrides the bottom portion, and the sample expands temporarily.

Photograph 1: Masado sample cured for 14 days after the reliquefaction test

5.2 Coefficient of earth pressure

Figures 7 and 8 are representative variation diagrams of the maximum $(\sigma_r/\sigma'_{v0})_{max}$ and minimum $(\sigma_r/\sigma'_{v0})_{min}$ values of the soil pressure constant during the initial liquefaction and reliquefaction tests.

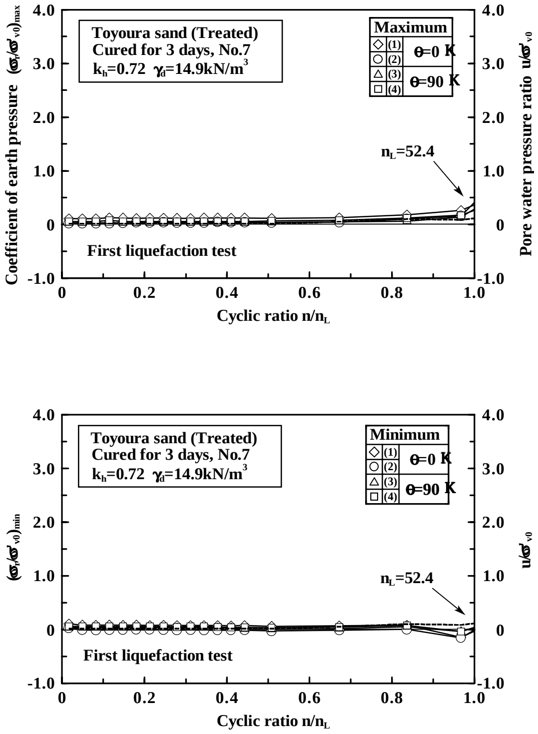


Figure 7(a): Changes in $(\sigma_r/\sigma'_{v0})_{max}$ and $(\sigma_r/\sigma'_{v0})_{min}$ for Toyoura sand sample cured for 3 days in the initial liquefaction test

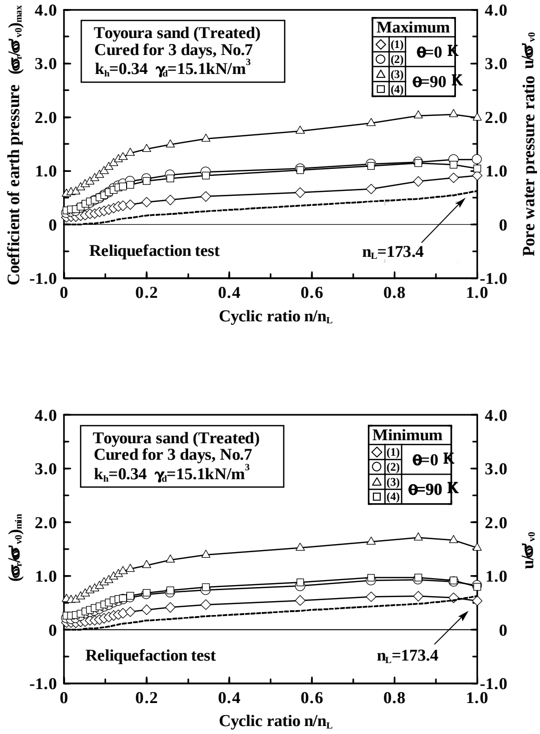


Figure 7(b): Changes in $(\sigma_r/\sigma'_{v0})_{max}$ and $(\sigma_r/\sigma'_{v0})_{min}$ for Toyoura sand sample cured for 3 days in the reliquefaction test

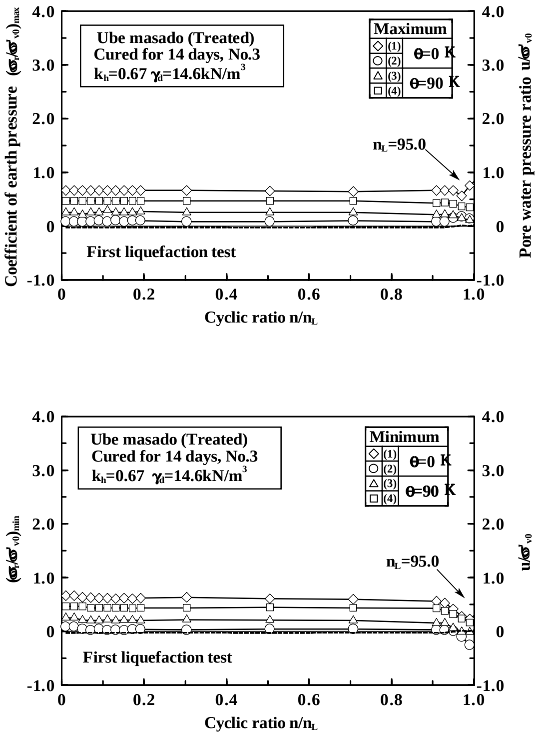


Figure 8(a): Changes in $(\sigma_r/\sigma'_{v0})_{max}$ and $(\sigma_r/\sigma'_{v0})_{min}$ for masado sample cured for 14 days in the initial liquefaction test

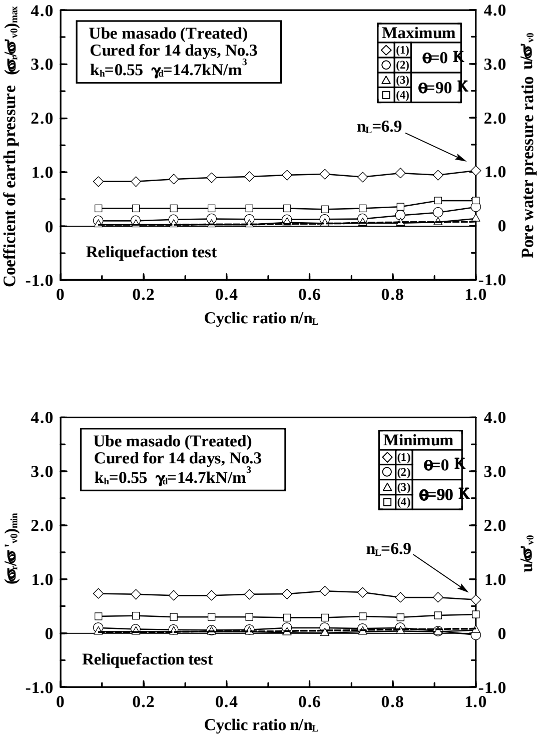


Figure 8(b): Changes in $(\sigma_r/\sigma'_{v0})_{max}$ and $(\sigma_r/\sigma'_{v0})_{min}$ for masado sample cured for 14 days in the reliquefaction test

(a) and (b) are representative diagrams for Toyoura sand samples cured for 3 days, and Figures 8 (a) and (b) are for masado samples cured for 14 days. Here, the (σ_r/σ'_{v0}) is the value obtained by dividing the horizontal stress σ_r produced in the sample during the cyclic shear by the initial effective vertical stress σ'_{v0}. The numbers (1) through (4) in the figures and the captions represent the points where horizontal stress was measured: (1) and (2) are parallel to the shaking direction, and (3) and (4) are perpendicular to the shaking direction. Both figures also show the pore water pressure ratio u/σ'_{v0}.

In these figures, the coefficient of earth pressure before shaking represents the coefficient of at-rest earth pressure K_0. When the curing time is 3 days, K_0 before shaking is almost zero, and it can be seen that the earth pressure reducing effect, which is the other improvement expected from the cement-treatment method, is obtained.

However, samples cured for more than 14 days have significantly high K_0 values. We believe this is the result of inappropriate curing conditions in the present experiment. In the present experiment, the sample is cured under vertical-stress loaded conditions, and water can be continuously supplied to the sample, so the sample is cured in a sealed condition. Therefore, hydration of the cement progresses, and the sample may have expanded. This increase in K_0 was not observed in samples cured for 1 or 3 days.

When we compare the soil pressure constants during cyclic shearing in Figures 7 and 8, we see that they sometimes exhibit smaller values than K_0 during the shaking. Soil particles in the sample are dislocated by shearing. During the shearing, the untreated soil samples and treated samples with short curing times undergo deformation according to the dislocation of the shear rings. As a result, horizontal stress is produced accompanying the deformation. However, samples cured for 14 days have high rigidity and do not experience the same amount of displacement as the shear rings. As a result, the sample and the surface of the loading plates separate, and horizontal stress decreases.

Before the second shaking, K_0 in cement-treated soils increase. As mentioned earlier, this is due to breaking of cement bonds between soil particles by the initial liquefaction and the generation of lateral stress.

6. CONCLUSION

In this study, we carried out shaking table tests to clarify the initial liquefaction potentials and the reliquefaction potentials of cement-treated sandy soils, and reached the following conclusions.

1) The reliquefaction resistances of cement-treated Toyoura sand and masado samples were lower than the initial liquefaction resistances. This is because the bonding between the soil particles is broken by the initial liquefaction. This was also proven by direct observation of the samples after the tests.
2) When cement-treated soil undergoes liquefaction in the first shaking, K_0 increases afterwards. This is also caused by the decrease in the bonding strength between the soil particles.
3) Samples cured for 3 days show a similar destruction mechanism to liquefaction of sandy soils. However, samples cured for 14 days cracks in the initial liquefaction, and destruction occurs at the boundary between the solid and liquid portions.

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