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A procedure to reach high liquefaction resistance in laboratory testing on reconstituted sand specimens by applying pre-shear history

Une procédure pour atteindre une résistance élevée à la liquéfaction dans les tests en laboratoire d'échantillons de sable reconstitué en appliquant l'historique de pré-cisaillement

Weichen Liu
Kajima Technical Research Institute, Kajima Corporation, Japan, liu@kajima.com
Department of Civil Engineering, University of Tokyo, Japan (Former Affiliation)

Junichi Koseki
Department of Civil Engineering, University of Tokyo, Japan

ABSTRACT: Studies in the past showed that the laboratory tests on reconstituted dense sand specimens sometimes 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 higher 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.

RÉSUMÉ: Des études antérieures ont montré que les essais en laboratoire sur des échantillons de sable dense reconstitué présentent parfois une résistance à la liquéfaction inférieure à l'intensité de champ observée in situ. Ce phénomène entraînerait un surdimensionnement excessif d'infrastructures importantes sur un sol sableux aussi dense. Par conséquent, dans cette étude, une série d'essais de cisaillement de torsion cylindrique creux non drainés cycliques ont été menés sur des échantillons de sable qui ont été préparés par la méthode de la pluie d'air avec une densité relative initiale élevée (environ 80%), avec plusieurs tentatives pour atteindre une résistance à la liquéfaction plus élevée. Au cours de ces essais de cisaillement en torsion, différents types d'historiques de pré-cisaillement ont été appliqués avant le chargement cyclique. Les résultats des tests ont montré que les échantillons avec pré-cisaillement utilisant une petite amplitude de déformation pouvaient présenter une résistance à la liquéfaction significativement élevée, par rapport à celui sans pré-cisaillement.

KEYWORDS: dense sand specimen, liquefaction, pre-shear history

1 INTRODUCTION

In the past, the study on liquefaction focused mainly on young sandy deposits or loose sandy ground where liquefaction resistance was thought to be low. However, during the construction of important infrastructures 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, it was reported that the liquefaction resistance of the in-situ frozen sample was significantly higher than that of tube samples and laboratory reconstituted specimens (Yoshimi et al. 1984 and Kiyota et al. 2009). 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 specimens that have similar behavior as the in-situ ground.

In the past, it was reported that liquefaction resistance was influenced by pre-shear histories (Ishihara & Okada 1978, Goto & Towhata 2014). 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.

2 TESTING METHOD

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

A hollow cylindrical torsional shear apparatus was employed, and its schematic figure is shown in Figure 2. 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 τ_{cyc} was reached.

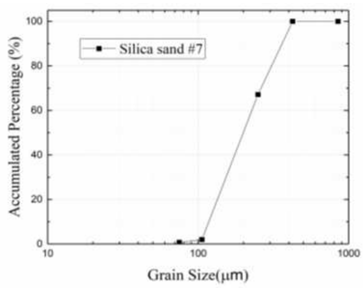

Figure 1. Grain size distribution of silica sand #7.

Table 1. Particle characteristics of silica sand #7.

Soil particle density, ρ_s	2.648 g/cm^3
Mean particle size, D_{50}	0.2 mm
Maximum void ratio, e_{max}	1.210
Minimum void ratio, e_{min}	0.700
Fines content, F_c	0%

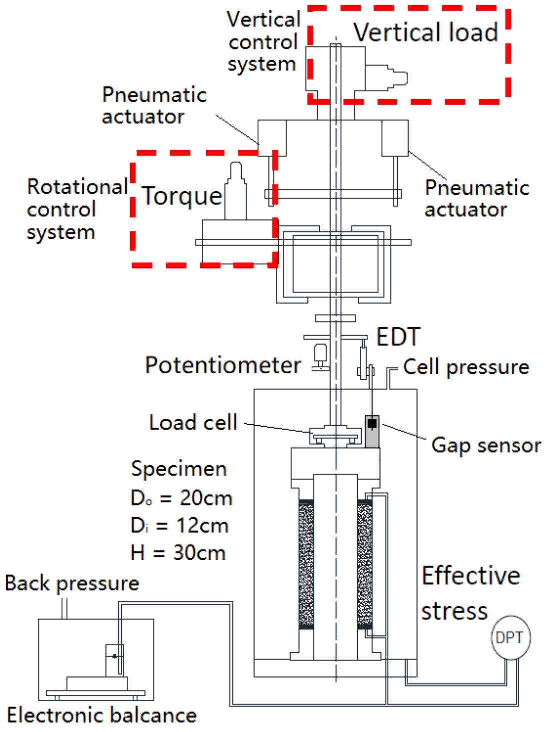

Figure 2. Schematic figure of the test apparatus.

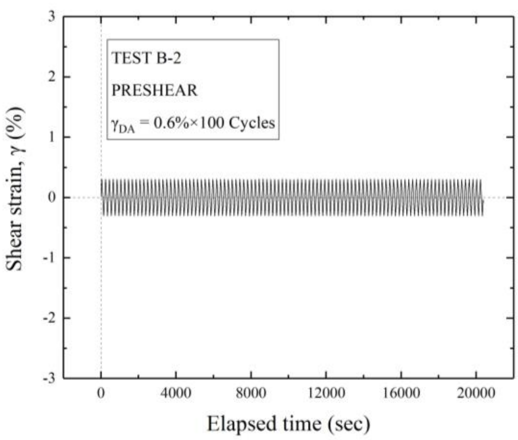

Figure 3. Time history of the shear strain of pre-shear under drained condition.

The hollow cylindrical specimen was prepared by the air-pluviation method to reach the initial relative density (D_{ri}) 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 (σ_0') of 100 kPa and the backpressure of 200 kPa. Then the cyclic torsional shear was conducted under undrained condition until the double amplitude of shear strain (γ_{DA}) reached 7.5% while the axial displacement was fixed to maintain a quasi-simple shear condition. After returning to shear strain (γ) of 0 and reconsolidation, the next stage of undrained cyclic torsional shear was conducted with the same cyclic stress ratio (CSR = τ_{cyc}/σ_0') as applied in the first cyclic loading.

In the cases with pre-shear histories, the pre-shear history was only applied after the initial isotropic consolidation. In all the cases except for B-2, the specimen was subjected to repeated liquefaction tests 3 to 5 times with the same CSR.

For cases with pre-shear under drained condition (Tests B-1~B-3), 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 the cases with pre-shear history under undrained condition (Tests C-1~C-6), the pre-shear history consists of several undrained cyclic loading stages. In these stages, cyclic torsional shear was applied until the excess pore water pressure ratio (Δu/σ_0') reached 0.5. Figure 4 shows the time history of excess pore pressure during one of the pre-shear stages as an example. Like the procedure of repeated liquefaction test, reconsolidation and repeated cyclic loading with the same target value of excess pore pressure were carried out repeatedly. Therefore, the test was started with an lower initial relative density and after it reached 79~80% by applying pre-shear histories introduced above, the liquefaction test was conducted with the cyclic stress ratio of 1.0 (Tests C-1~C-3) and other values (Tests C-4~C-6).

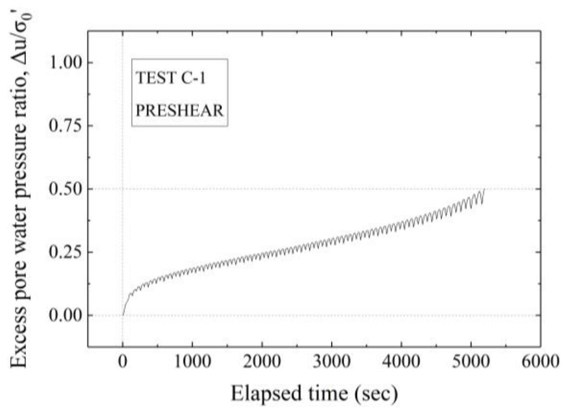

Figure 4. Time history of the excess pore water pressure ratio (Δu/ σ_0') in one of the undrained pre-shear stages.

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 Figures 5 and 6, respectively. The liquefaction resistance curve indicated by the relationship between cyclic number to reach the maximum double amplitude of shear strain ($\gamma_{(DA)}$) of 7.5% and CSR is shown in Figure 8. The relationship between relative density and number of cycles to reach the maximum double amplitude of shear strain (denoted as liquefaction resistance) is shown in Figure 8. Based on the results shown in Figure 8, it can be concluded that the repeated liquefaction and reconsolidation histories resulted in the increase of relative density as well as the liquefaction resistance.

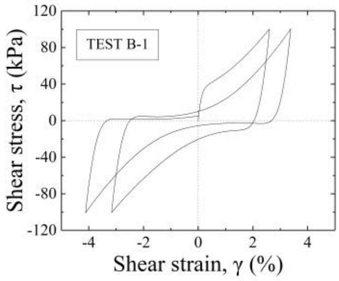

Figure 5. Effective stress path.

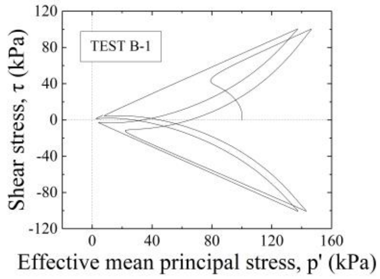

Figure 6. Stress-strain relationship.

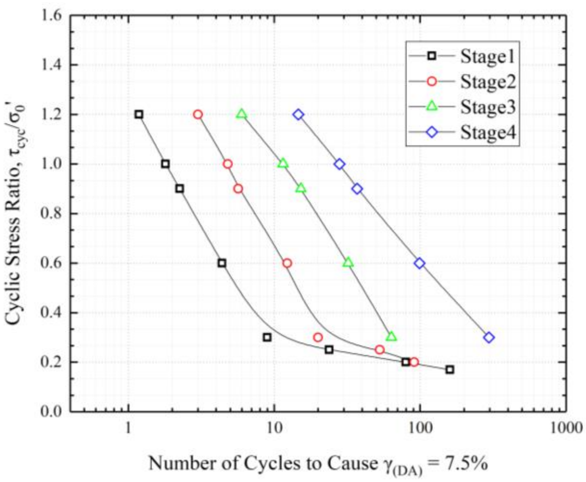

Figure 7. Liquefaction resistance curve of all liquefaction stages.

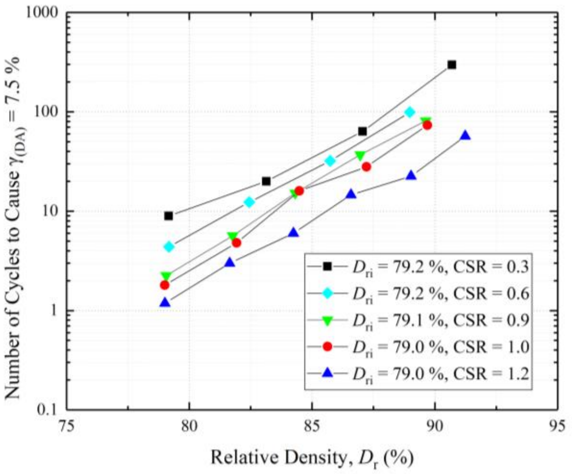

Figure 8. Relationship between relative density and liquefaction resistance (without liquefaction history).

3.2 *Repeated liquefaction test with various kinds of pre-shear histories*

In order to investigate the influence of pre-shear history, liquefaction tests with different pre-shear histories were carried out with the same CSR of 1.0, except for Test series C (with the same pre-shear history but different values of CSR). 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 $\gamma_{(DA)}$ of 7.5%).

Figure 9 shows the relationship between relative density and liquefaction resistance of all liquefaction stages of all the cases with CSR of 1.0 listed in Table 2. Figure 10 shows the liquefaction resistance of the 1st stage of all cases with pre-shear histories as well as that of cases without pre-shear history.

3.2.1 *Pre-shear history under drained condition*

The results of cases with pre-shear histories under drained condition in series B 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 immediately after the pre-shear. In other words, it can be noticed that the liquefaction resistance in the 2nd stage reduced to a similar value of the case without pre-shear history.

Table 2. Details of cases with pre-shear histories.

Test ID	Details of pre-shear history	CSR	$N_{c1}(\gamma_{(DA)}$ = 7.5%)
A-1	No pre-shear	1.0	1.8
B-1	γ_{DA} = 0.2%×100 cycles, drained	1.0	2.2
B-2	γ_{DA} = 0.6%×100 cycles, drained	1.0	3.4
B-3	γ_{DA} = 0.6%×200 cycles, drained	1.0	15.3
C-1	Δu/ σ_0' = 0.5×1 stage, undrained	1.0	3.1
C-2	Δu/ σ_0' = 0.5×10 stages, undrained	1.0	16
C-3	Δu/ σ_0' = 0.5×20 stages, undrained	1.0	75.3
C-4	Δu/ σ_0' = 0.5×20 stages, undrained	0.9	143
C-5	Δu/ σ_0' = 0.5×20 stages, undrained	1.2	36.5
C-6	Δu/ σ_0' = 0.5×20 stages, undrained	1.6	19.8

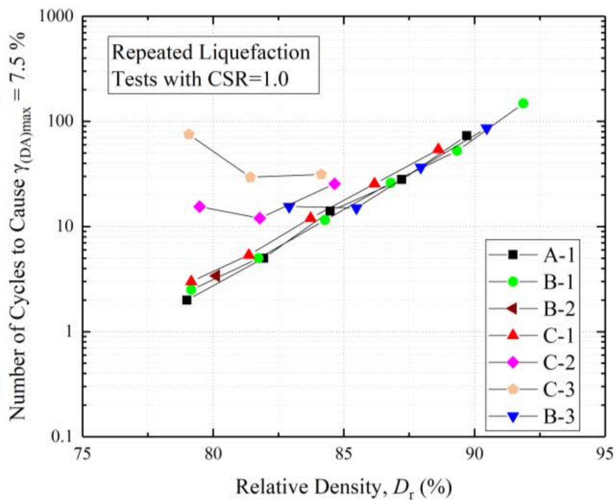

Figure 9. Relationship between relative density and liquefaction resistance.

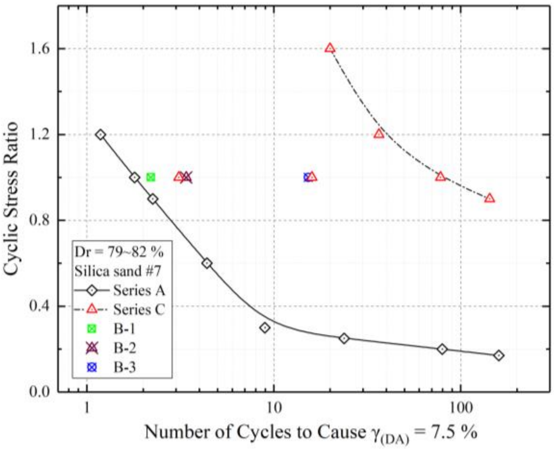

Figure 10. Liquefaction resistance in the 1st stage of all cases.

3.2.2 *Pre-shear history under undrained condition*

As introduced above, test series C were carried out with pre-shear history under undrained condition.

The test result in Test C-1 showed a significant increase in liquefaction resistance after this kind of incomplete liquefaction histories (excess pore water pressure generated but not enough to cause full liquefaction). In order to verify the accumulation possibility of the pre-shear effect during these multiple pre-shear stages, Tests C-2 and 3 were carried out with different number of pre-shear stages, and liquefaction tests after pre-shear were conducted with the same condition as in Test C-1.

As shown in Figure 10, the liquefaction resistance of the first stage were increased in different levels due to different stage numbers of pre-shear. Similarly, to series B, liquefaction resistance decreased after the first stage of the liquefaction test. However, unlike series B, the accumulated pre-shear effects were not fully eliminated.

Tests C-4~C-6 were conducted with the same pre-shear history as Test C-1 but with different CSRs during liquefaction tests, and they showed extremely high resistance compared with those of series A as shown in Figure 10. Figures 11 and 12 show the stress-strain relation and effective stress path of each one case in series A and C, respectively. In Test A-7, the accumulation speed of shear strain was quite different before and after initial liquefaction occurred. While in Test C-1, due to the influence of pre-shear, shear strain in the first cycle was very large and then it began to increase gradually with the accumulation of excess pore water pressure.

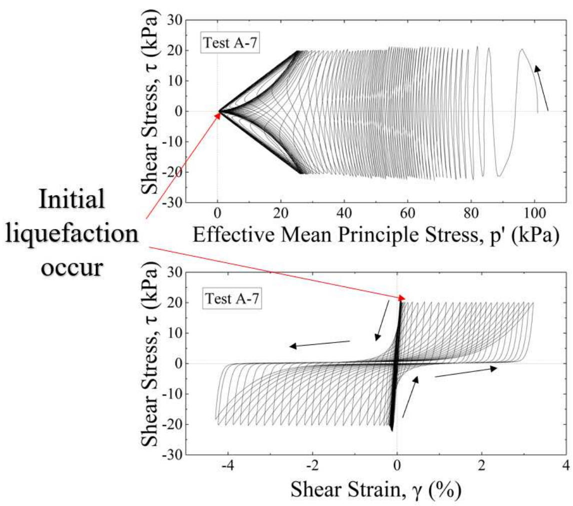

Figure 11. Stress-strain curve and effective stress path of test A-7.

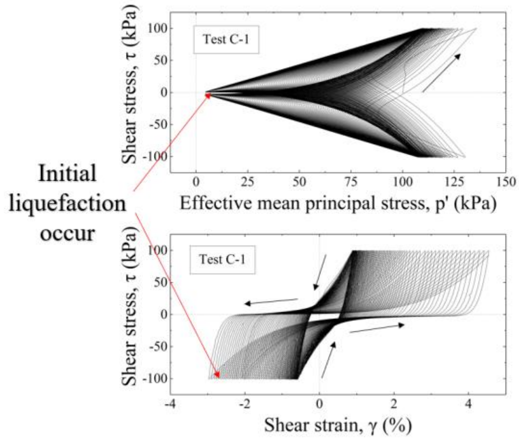

Figure 12. Stress-strain curve and effective stress path of test C-1.

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 γ_{DA} = 0.2 to 0.6% under drained conditions increase the liquefaction resistance of the sand specimen. The degree of resistance 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 1st liquefaction stage immediately after that.

3) Pre-shear with several stages of incomplete liquefaction histories under undrained condition were found to increase the liquefaction resistance significantly. The influence of pre-shear declined after the 1st stage of liquefaction test but not fully eliminated.

4) Accumulation of shear strain as well as excess pore water pressure during liquefaction stage were affected by the pre-shear history.

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

5 ACKNOWLEDGEMENTS

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