Silica Sand Behavior under Repeated Liquefaction in Cyclic Triaxial Test

Comportement des sables de silice soumis à des liquéfactions répétées lors d'essais cycliques triaxiaux

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ABSTRACT: A series of repeated liquefaction tests were conducted on silica sand with number seven grading in triaxial apparatus in order to study its behavior in terms of stress history, strain history and small strain history effect. Sudden reduction in effective stress was observed in the early liquefaction stages, which corresponds with high axial strain accumulation. This reduction became less in the following stages. In stress history effect study, an increase in repeated liquefaction resistance in terms of number of cycles to liquefaction was found. Liquefaction resistance curve was created and similar shape among different liquefaction stages was observed. This paper also studied the effect of double amplitude axial strain history on the liquefaction resistance by conducting cyclic undrained test at various strain histories. It is obvious that low strain histories, i.e. 1% and 2%, show higher liquefaction resistance even though they have smaller increase in density. Moreover, small strain effect study, less than 1%, revealed that liquefaction resistance tends to depend only on the latest liquefaction history.

RÉSUMÉ : Une série de tests de liquéfactions répétées a été réalisée sur du sable de silice numéro 7 à l'aide d'un appareil triaxial afin d'étudier son comportement en terme d'histoire des contraintes, des déformations et des faibles déformations. Une soudaine réduction des contraintes effectives a été observée dans les premières phases de liquéfaction et correspond à une forte accumulation de déformations axiales. En étudiant l'effet de l'histoire des contraintes, la résistance à la liquéfaction en terme de nombre de cycles avant liquéfaction tend à croitre et apparait avec des phases de liquéfaction plus élevées. L'effet de l'histoire des déformations d'amplitude double sur la résistance à la liquéfaction a été étudié lors d'essais cycliques non drainés à différents stades de déformation. Les cas de faibles déformations subies au cours de l'histoire (1% et 2%) présentent une résistance supérieure à la liquéfaction même avec une plus faible augmentation en densité. L'étude sur l'effet de faibles déformations (inférieure à 1%) a révélé que la résistance à la liquéfaction tend à ne dépendre que de la plus récente liquéfaction.

KEYWORDS: repeated liquefaction, triaxial, silica sand

1 INTRODUCTION

Liquefaction phenomenon was first recognized in the event of Niigata earthquake in Japan in 1964, which vastly caused damage to many civil engineering structures. Since then, the topic of liquefaction interested many geotechnical researchers and engineers. However, in the past few decades, there have been many reports in many countries; for instance, Japan, New Zealand and Greece that liquefaction phenomena took place again where liquefaction had already occurred (e.g. Kuribayashi and Tatsuoka 1975, Wakamatsu 2012, Cubrinovski et al. 2012, Yamada et al. 2011, and Papathanssiou et al. 2005). These example case studies not only show that liquefaction can be reoccurred but also may even cause more severe damage to the civil structures. Thus, although liquefaction densifies soil, soil liquefaction resistance may not become greater.

Soil repeated liquefaction phenomena, or sometimes called as multiple liquefaction or reliquefaction, means that soil liquefies from time to time at the same spot, which induced by earthquakes or following aftershocks. In many cases, it is not necessary that repeated liquefaction occurs during the same event of earthquake but also within a long period of time where dissipation of previously generated excess pore water pressure and soil reconsolidation has already occurred.

Recently, the issue of repeated liquefaction phenomena has been being studied intensively by using both element test and model test; for example, shaking table test, triaxial test and torsional shear test. In Japan, Toyoura sand is frequently selected to be a sample for element tests; however, as a substitute for Toyoura sand due to its availability and high cost, silica sand with number seven grading is also occasionally used in model test. As a result of material difference, data from these two types of test is difficult to compare although their physical properties are similar. In order to confirm behavior of silica sand with number seven grading under element testing, this paper presents result of a series of repeated liquefaction tests using the silica sand in a triaxial apparatus.

2 MATERIALS

In this research, silica sand with number seven grading was used. It is generally artificial sand produced from crashed rock. The one with number seven grading is uniformly distributed, poorly graded sand and its grain size distribution is similar to Toyoura sand. The properties and its cumulative grain size distribution are shown in Table 1 and Figure 1, respectively together with Toyoura Sand.

Table 1. Properties of silica sand with number seven grading and Toyoura sand

Properties	*Silica Sand no.7*	*Toyoura Sand*
Specific gravity	2.640	2.656
Maximum void ratio, e_{max}	1.243	0.992
Minimum void ratio, e_{min}	0.743	0.632
Mean Particle Diameter, D_{50} (mm)	0.206	0.190

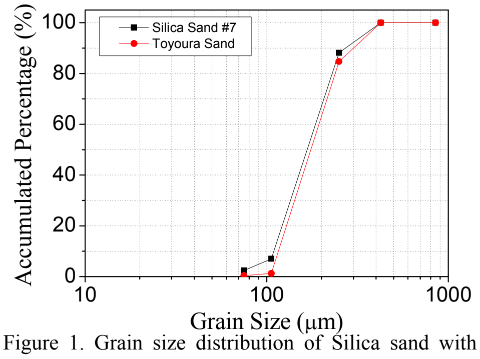

Figure 1. Grain size distribution of Silica sand with number seven grading and Toyoura sand

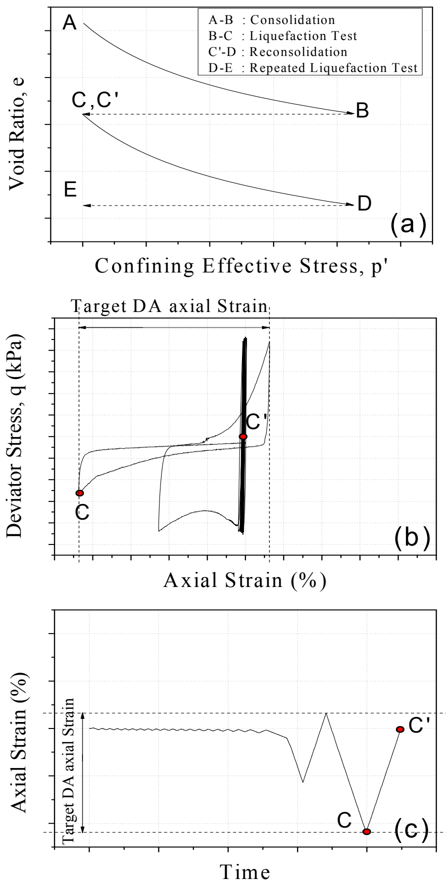

Figure 2. Liquefaction Test stages (a) schematic change in void ratio; (b) stress-strain relationship; (c) axial strain time history

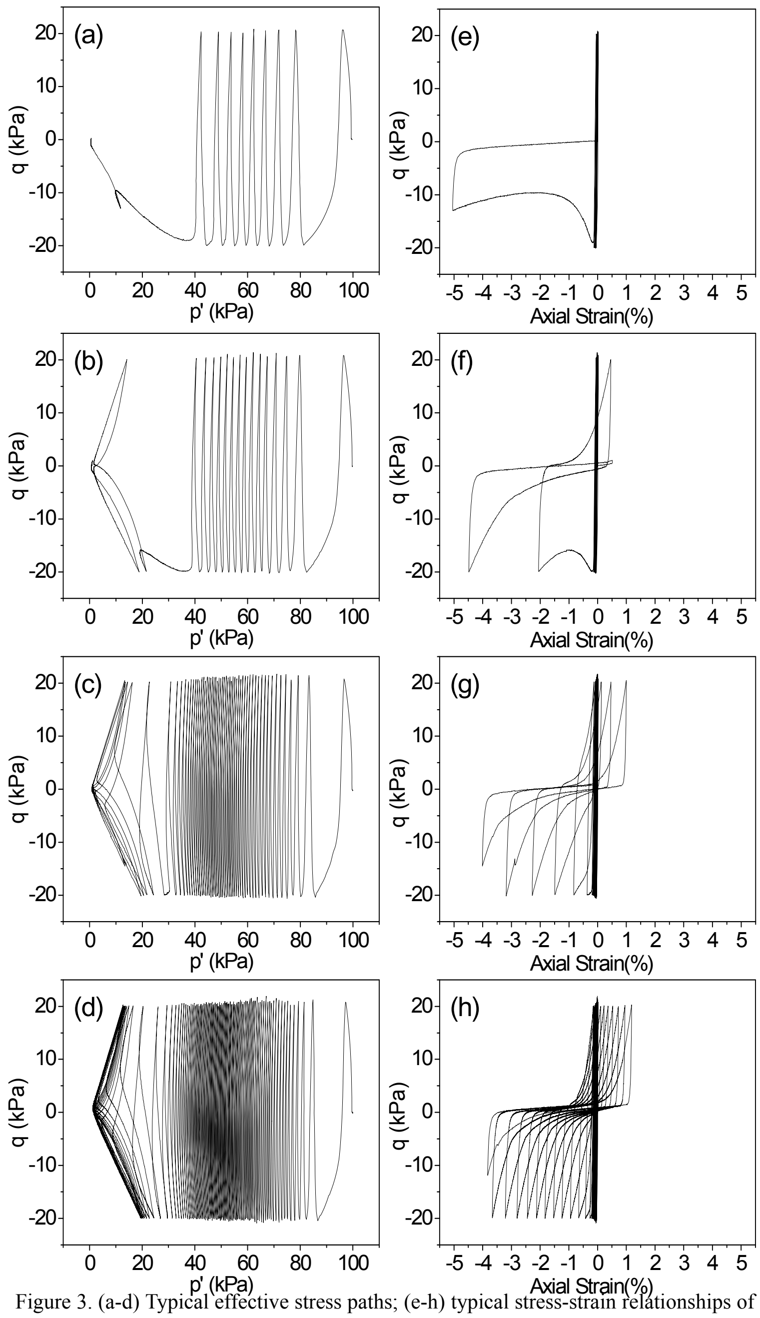

Figure 3. (a-d) Typical effective stress paths; (e-h) typical stress-strain relationships of liquefaction test for stages 1-4

3 METHODOLOGY

3.1 *Specimen preparation*

Air-pluviation method was used to prepare specimen by free falling the sand particles from a nozzle to a mold of 150mm high and 75mm in diameter. This nozzle allows constant flow rate of material accumulating from the bottom of the mold to the top. Uniform target relative density (Dr) can be achieved by adjusting drop-height, which was maintained constant throughout the pluviation process. The process continued until material overfills a mold. The top specimen surface was then leveled by scraping with a thin plate so that the material inside a mold remains undisturbed. Two porous stones were placed at the top and the bottom of specimen. Confining pressure of 30 kPa was then applied in order to keep the specimen in cylindrical shape. Specimen saturation was performed by double vacuum method (Ampadu and Tatsuoka 1993). Before starting water flow, specimen was left vacuuming at least 1.5 hour to ensure that air bubble is enlarged and is sucked out. Consequently, Skempton's B-value became over 0.95. It must be noted that counter weight balance of loading piston was employed to avoid specimen disturbance during specimen preparation.

3.2 *Consolidation*

The testing procedure for this repeated liquefaction test is schematically illustrated in Figure 2. After ensuring degree of saturation by confirming the B-value over 0.95, specimen was then isotropically consolidated from a confining pressure of 30 kPa to that of 100 kPa as shown from stage A to Stage B in

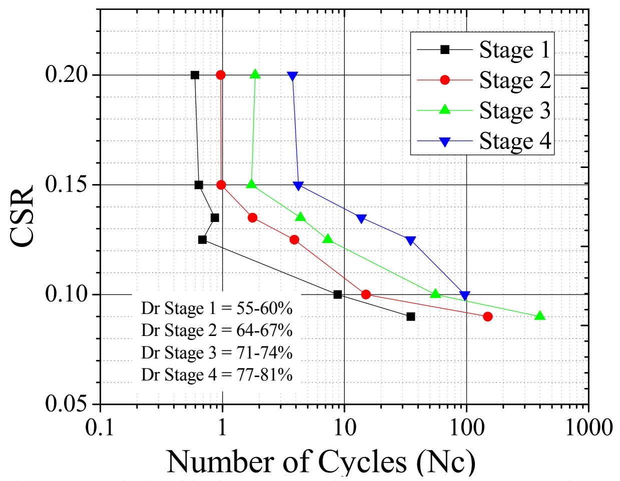

Figure 4. Relationship between cyclic stress ratio (CSR) and number of cycles to liquefaction at 5% DA axial strain

Figure 2a. An increasing rate of pressure should be small, in this case 5 kPa/min, so that deviatoric stress can be maintained at 0 kPa by controlling simultaneously the axial loading system. Consequently, specimen was left for consolidation time of 15 minutes before subjecting to liquefaction test.

3 .3 *Liquefaction Test*

Following equation 1, the single amplitude of cyclic deviator stress, q, can be computed by setting the target value of cyclic stress ratio (CSR). It is noted that initial effective confining stress (σ'_c), in this research, was always 100 kPa in all test series. By applying cyclic loading under undrained condition, excess pore water pressure was gradually generated accompanied by axial strain accumulation. Generally, liquefaction occurs when zero effective stress condition is met; i.e. excess pore water pressure becomes equal to the initial effective confining stress. However, the liquefaction stage in this research was defined based on the double amplitude (DA) axial strain percentage. Once, a specified amount of DA axial strain is reached, the cyclic loading stops and the left over strain is adjusted back to initial value, i.e., 0%, which usually corresponds with zero effective stress as shown from Stage C to Stage C' in Figure 2. After that, excess pore water pressure was released allowing dissipation and reconsolidation by opening specimen drainage valve (Stages C' to D). Similar to the initial consolidation process, it is noted that the valve must be opened slowly in order to maintain isotropic condition. Reconsolidation time was five minutes before the next liquefaction test. In addition, it is ensured that cyclic loading is terminated on the extension side; i.e. negative axial strain, in order to unify possible effects of induced anisotropy. An example of repeated liquefaction test result in terms of effective stress path and stress-strain relationship is shown in Figure 3.

Repeated Liquefaction test in a triaxial apparatus is limited up to 3-4 stages because of reconsolidation process which causes a change in specimen density and volume promoting a change in specimen shape. This non-cylindrical shape results in a non-uniform confining stress applied to the specimen. Nonetheless, it also depends on DA strain since the larger of the DA strain is, the larger decrease in specimen volume is expected.

In this research, liquefaction test is divided into three series to study the effect of stress history, strain history and small strain history by varying some testing parameters. The result of liquefaction resistance is compared in terms of number of cycle to liquefy.

$$CSR = \frac{q}{\sigma'_c} \qquad (1)$$

4 RESULTS AND DISCUSSION

4 .1 *Repeated liquefaction test with constant DA axial strain*

This series of test focuses on the issue of stress history effect on liquefaction resistance. There were in total 6 liquefaction tests at difference CSR values ranging from 0.09 to 0.20. Each test was carried out up to 4 liquefaction stages, while keeping the same CSR as in the first stage. Initial relative density of specimen was about 50-55%; however, due to consolidation process, relative density prior to the first cyclic loading was approximately 55-60%. The specimen density was continuously raised with liquefaction stages because of reconsolidation process. In each stage, liquefaction is defined as 5% DA axial strain. Liquefaction resistance was computed in terms of number of cycles to liquefy (Nc). An example of effective stress path and stress-strain relationship at each liquefaction stage is shown in Figure 3. It can be seen that in the early stage, there is sudden decrease in mean effective stress (p'), which is corresponding with large axial strain accumulation. This p' reduction becomes gradually less in the following stages. Liquefaction curve, in terms of Nc and CSR, is presented in Figure 4. In every test, liquefaction resistance of silica sand with number seven grading increased with liquefaction stages. In case of small CSR value of 0.9, the specimen did not reach liquefaction stage in the fourth stage because of high density and low cyclic stress amplitude.

4 .2 *Repeated liquefaction test with various DA axial strain*

The objective of this test is to study the effect of strain history on liquefaction resistance. Repeated liquefaction tests were conducted with the same value of CSR at 0.11 and various DA axial strain histories; e.g. 1%, 2%, 5%, 7% and 10%. In the following stages, the test was terminated at the same DA axial strain as in the previous stage. Therefore, the only difference between each test was DA axial strain history. Due to difference in DA axial strain in each test, number of cycles was calculated at the lowest DA axial strain of 1%.

Relative density change of each stage is shown in Figure 5. It can be seen clearly that this change depends on DA axial strain history. The larger the DA axial strain is, the larger change in relative density is observed. Liquefaction resistance curve in terms of number of cycles to liquefaction at 1% DA axial strain and relative density are presented in Figure 6. At second and third stages, although strain history of 1% and 2% produced relatively much smaller increase in relative density than the others, their liquefaction resistances are much greater. However, random trend was found in strain histories over 5%. This behavior is different from that of Toyoura sand where consistent agreement in liquefaction resistance and strain history over 5% was also found (Wahyudi et al. 2015). However, it can be seen that at small DA axial strain, the influence of relative density becomes minor. It is more governed by DA strain history.

4 .3 *Repeated liquefaction test with small strain history*

This test series is aimed to investigate the effect of small strain history (so called 'pre-shearing') on liquefaction resistance. In the first stage, DA small axial strains of 0.1%, 0.2% and 0.5% were applied to the specimens followed by 2% DA axial strain history in the following stages (up to four stages). Repeated liquefaction resistance of this test series in terms of number of cycles to liquefy and relative density is presented in Figure 7 together with result of 2% DA axial strain history in previous test series. In the second liquefaction stage after small strain application, liquefaction resistance sharply increased with small increase of relative density. This is also corresponding with the previous test series as discussed in 4.1 and 4.2. In the third stage, when 2% DA axial strain was applied, liquefaction resistance was found to decrease and join 2% DA axial strain history result. Liquefaction resistance again increased in the fourth stage after subjected to 2% DA axial strain. They also have similar increasing resistance trend to those with the 2% DA axial strain history. This may imply that liquefaction resistance is only influenced by the immediate-past liquefaction history.

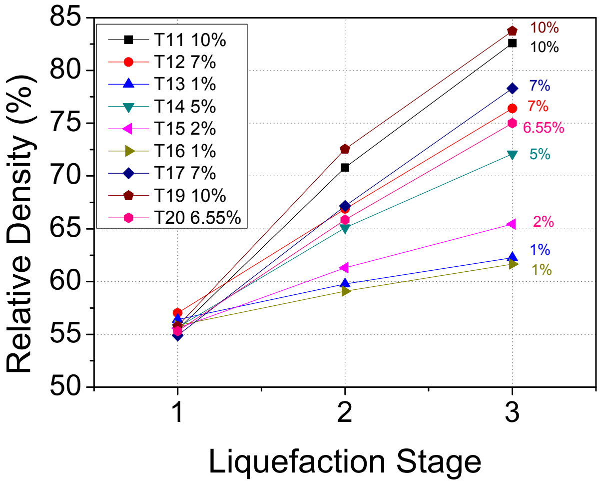

Figure 5. Change in relative density during repeated liquefaction tests at different levels of DA axial strain

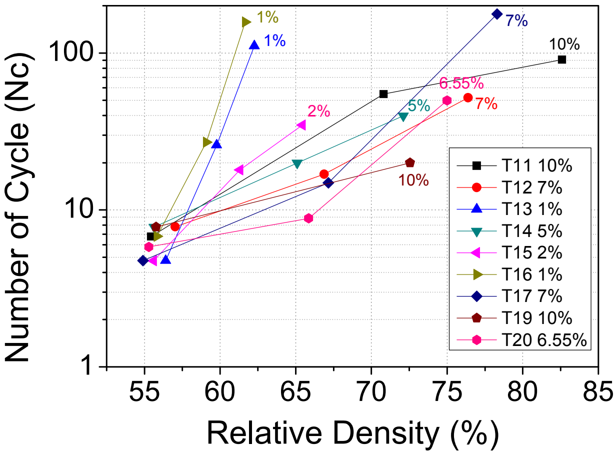

Figure 6. Relationship between number of cycles to cause liquefaction (i. e. DA axial strain = 1%) and relative density during repeated liquefaction test

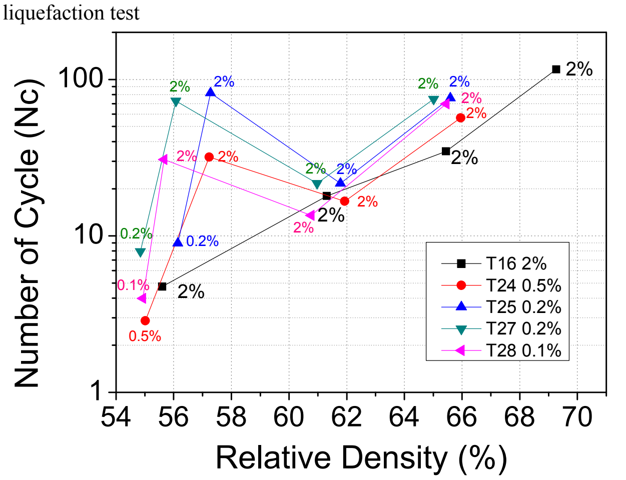

Figure 7. Relationship between number of cycles to cause liquefaction of pre-sheared specimens during repeated liquefaction test

5 CONCLUSION

In order to investigate repeated liquefaction behavior of silica sand with number seven grading, three series of undrained cyclic triaxial tests were performed. The summary of the main conclusions in this study are as follow;

1. In the first series, the undrained cyclic tests were conducted under various CSR with constant DA axial strain at 5%. Sharp decrease in mean effective stress was found in the initial stage which gradually bcome less in the following stages. Soil resistance against repeated liquefaction increases with number of liquefaction stages. Similar trend of relationship between CSR and number of cycles to liquefation can be found among different stages.
2. In the second test series, the specimens were subjected to undrained cyclic loading at constant CSR but various DA axial strain histories. Results showed that specimens which subjected to low DA axial strain (1% and 2%) gained relatively higher liquefaction resistance than the others even though their relative density slightly increased. This may imply that the liquefaction resistance is more influenced by strain history than by density. However, under over 5% of DA axial strain, a random trend was found.
3. In the final series, specimens were first undrained cyclic loaded at various small DA axial strain levels (0.1%-0.5%) followed by 2% DA axial strain in the following liquefaction stages. Liquefaction resistance was observed to be sharply increased in the second stage after subjected to small strain histories in the previous stage which supports conclusion number 3.
4. Again in the third series, soil resistance dropped in the third stage of liquefaction altought they showed relatively high resistance in previous stage due to pre-shearing history. This can be concluded that liquefaction resistance depends on only immediate-past liquefaction history.

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