EFFECTS OF PRE-SHEARING HISTORY ON REPEATED LIQUEFACTION BEHAVIOR OF SAND USING STACKED-RING SHEAR APPARATUS

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ABSTRACT: Countless researchers have been studying the liquefaction phenomenon. However, few of them were focusing on the experimental studies of the soil repeated liquefaction behaviors. Re-liquefaction has become an increasing concern among researchers since the 2011 Great East Japan Earthquake Disaster revealed about 60 re-liquefied sites around Japan. Unlike triaxial apparatus, the stacked-ring shear apparatus used in this study is capable of performing virtually unlimited number of re-liquefaction stages. The tests observed in the loose and dense sands could reveal the significance of effects of pre-shearing history on the re-liquefaction behavior of sand. Larger shearing history during the previous liquefaction may lead to greater changes in soil particle structure, thus re-liquefaction resistance becomes weaker. In the early stages of re-liquefaction, the change in soil particle structure is more predominant than the increase in the density induced by re-consolidation after the liquefaction. However, in the later stages, soil density may regain its strength and the soil might not liquefy under the same condition.

Key words: Re-liquefaction, stacked-rings, pre-shearing, specimen’s density.

INTRODUCTION

Liquefaction is a unique phenomenon in which geo-material behaves more-like a liquid than solid, thus completely loss its resistance. This phenomenon generally is found when geo-material is subjected to the cyclic forces in undrained condition such as earthquake. During rapid cyclic loading, pore water pressure could not dissipate easily. As a result, the effective stress of soil decreases towards zero, in which virtually there is no contact between each soil particle.

There were countless studies on liquefaction that have been conducted by previous researchers. They investigated various aspects that may affect the behaviors of liquefied soil and the behaviors of soil in post-liquefaction. Among those studies, few of them investigated the experimental study on re-liquefaction phenomenon, in which soil can liquefy repeatedly from one time to another. It was found that the behavior of re-liquefied soil is largely affected by the pre-shearing history applied in the previous liquefaction. Such pre-shearing history includes the pre-seismic history (Finn et al., 1970 and Seed et al., 1970), stress history (Ishihara and Okada, 1972), pre-shearing history (Ishihara and Okada, 1978), past history of rotation of the principal stress (Towhata and Ishihara, 1985). The other frontier studies discussed about the effects of over-consolidation history (Ishihara and Takatsu, 1979) and liquefaction-induced settlement (Ishihara and Yoshimine, 1992). The limited number of experimental studies in this particular topic was possibly due to the limitation of the test apparatus itself. General

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triaxial and hollow cylinder torsional shear apparatuses are hardly able to maintain the shape of the specimen once it liquefies. Therefore, in the previous experimental studies, the investigation of re-liquefaction (multi-stage liquefaction) could be made mostly up to two stages. There is also an assumption that once the soil liquefied, then its resistance against re-liquefaction will always be stronger. This assumption is based on the densification of soil that takes place in post-liquefaction, thus the soil resistance is expected to become stronger against re-liquefaction in the future earthquakes. Wakamatsu (2010) reported that liquefaction re-occurred at 150 sites during the period from year of 745 to 2008 throughout Japan. Wakamatsu (2012) also reported that in the 2011 Great East Japan Earthquake Disaster alone, at least 60 cases of soil re-liquefaction were found. Those areas which are prone to liquefy repeatedly are the areas where large deposit of young sandy soil exists such as reclaimed land, areas along river and river delta. These evidences raised concern among researchers about the potential danger of re-liquefaction that might happen in the future big earthquake.

In the recent study on the re-liquefaction resistance of sand, Yamada et al., (2010) showed that re-liquefaction resistance may or may not increase even when the soil became denser and denser in the following liquefaction stages. The primary reason of this phenomenon was due to the increase of soil anisotropy induced by the pre-shearing history from previous earthquakes. They performed up to 4 stages of re-liquefaction test by using triaxial apparatus.

This paper is aimed to investigate the behaviors of re-liquefied sand using a newly developed machine so called stacked-rings shear apparatus. Unlike the tests conducted in triaxial or hollow cylinder torsional shear apparatuses, the stacked-rings shear apparatus is capable of maintaining the shape of the specimen to remain constant even under very large deformation. By taking such advantage it can perform not just a few number of re-liquefaction stages, but virtually unlimited number of re-liquefaction stages with a single specimen.

EXPERIMENT PROCEDURES

The outline of the newly developed machine so called stacked-ring shear apparatus is shown in Fig. 1. The vertical load is applied to the specimen through a pneumatic system with bellofram cylinder while the torque is applied to the specimen through a direct motor system. This direct motor system allows the apparatus to virtually apply endless rotation in both clockwise and anti-clockwise directions. Both vertical stress and torque are measured at the top cap connected to the load cell. In the current setting of the apparatus, the capacity of vertical load and torque are 30 kN and 1500 N.m, respectively.

In the stacked-ring shear apparatus, an annular specimen is placed in between two parts of stacked-rings, which are inner and outer parts as shown in Fig. 2(a). Each inner and outer part is composed of 31 pieces of vertically-stacked annular rings having a thickness of 5 mm as shown in Fig. 2(b). It needs to be mentioned that there is no direct contact between the rings. Six pieces of metal bearings with a thickness of 0.1 mm were inserted in between the rings, so that friction can be reduced as minimum as possible. This 0.1 mm gap between the rings is small enough to ensure the sand particles with a mean diameter larger than 0.1 mm (D_{50} > 0.1mm) will not extrude during shearing. Each ring is allowed to move in circumferential direction, while it is restrained in the vertical direction. The inner and outer diameters of the specimen are 90 mm and 150 mm, respectively, and the height of the specimen is 155 mm.

Toyoura sand was used as the test material. Its particles have an angular or sub-angular shape with the following physical properties: specific gravity, G_s=2.656; mean diameter, D_{50}=0.162mm; fines content, F_c=0.1%; max. void ratio, e_{max}=0.992; min. void ratio, e_{min}=0.632. Specimens were prepared by pluviation of air-dried sand particles into a mold through air. Their falling height was kept constant throughout the pluviation process in order to obtain specimens with highly uniform density.

Four series of tests are presented in this paper. The first two series were aimed to investigate the effects of pre-shearing history on the re-liquefied sand. These two series of tests were tested with specimens having an initial relative density of about Dr_0= 55% (e_0=0.793) and Dr_0= 80% (e_0=0.702), which corresponds to loose and dense packing, respectively. To apply the pre-shearing history to the specimens, each of them was sheared with pre-fixed shear strain double amplitude. For comparison purpose, the other two series of tests were conducted as single stage liquefaction tests under various densities as a reference. The testing conditions for each series of test are summarized as follows:

1. Re-liquefaction test on loose sand (Dr_0=55.0%) sheared with maximum shear strain double amplitudes ($\gamma_{DA.max}$) of 2%, 4%, 7% and 10% with cyclic shear stress ($\tau_{cy.}$) of 10 kPa.
2. Re-liquefaction test on dense sand (Dr_0=80.0%) sheared with maximum shear strain double amplitudes ($\gamma_{DA.max}$) of 2%, 3%, 4%, 5% and 10% with cyclic shear stress ($\tau_{cy.}$)of 20 kPa.
3. Virgin liquefaction test with various relative densities sheared with cyclic shear stress of 10 kPa.
4. Virgin liquefaction test with various relative densities sheared with cyclic shear stress of 20 kPa.

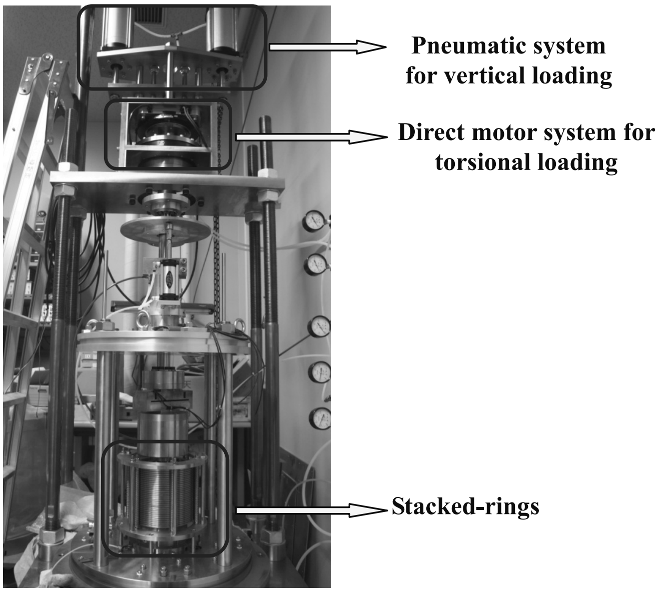

Fig. 1: Stacked-rings shear apparatus

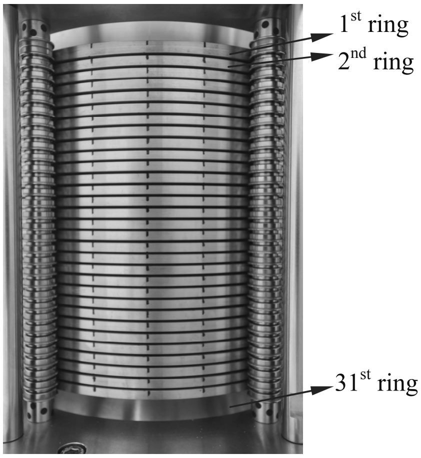

Fig. 2(a): Detail of stacked-rings

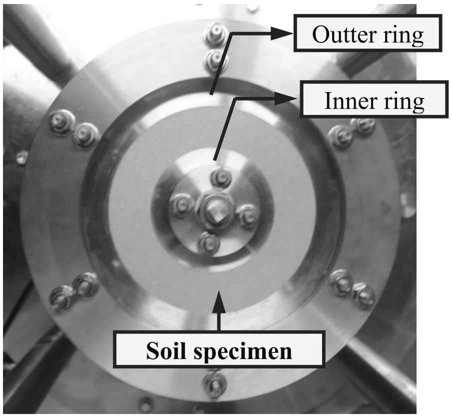

Fig. 2(b): Plan view of stacked-rings

Figures 3(a) and Fig. 3(b) show the sequences to conduct a re-liquefaction test in this study. Prior to the application of cyclic shear loading, each specimen was consolidated one-dimensionally up to vertical stress of 200 kPa as shown on state B. Then, the specimen was subjected to cyclic shear stress ($\pm\tau$) under constant volume condition. The liquefaction was defined as the state whenever the double amplitude of shear strain reached 2.0%, while the cyclic loading was continued to achieve the pre-fixed $\gamma_{DA.max}$ value (state C). Then, the stage of liquefaction was completed by adding another half cycle of shear loading from state C to state C', where the shear strain (γ) is equal to zero as shown in Fig. 3(c) and 3(d). State C' in this study was set to be the starting and the ending states of each stage during re-liquefaction test. The next liquefaction stage was started by re-consolidating the liquefied specimen into their original effective vertical stress (σ_v') of 200 kPa at state D. Then, the liquefaction test continued following the same procedure as the one described in the first liquefaction stage.

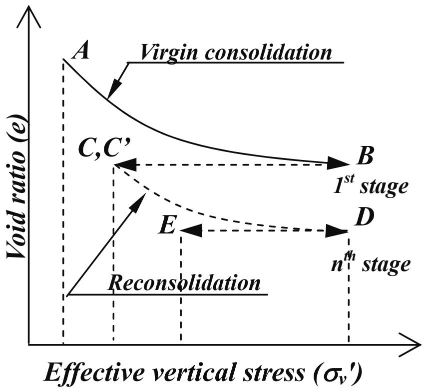

Fig. 3(a): Typical void ratio and vertical stress relationship in re-liquefaction test

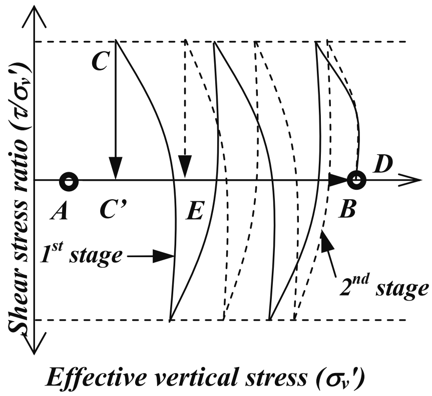

Fig. 3(b): Typical shear stress ratio and vertical stress relationship in re-liquefaction test

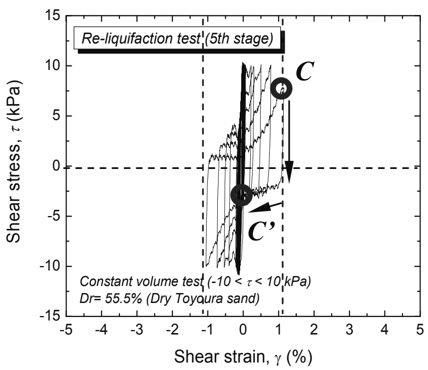

Fig. 3(c): Typical shear stress and shear strain relationship in one stage of re-liquefaction test

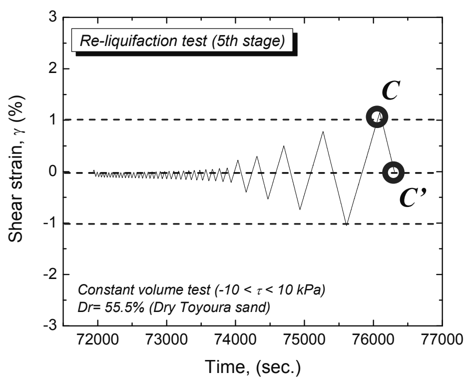

Fig. 3(d): Typical shear strain and time relationship in one stage of re-liquefaction test

The liquefaction resistance was evaluated by evaluating the number of cycles needed to reach the double amplitude of shear strain 2.0%, using the equation shown below.

$$N\gamma_{DA} = \frac{\left(\gamma_{DA} - \gamma_{DA(Ni)}\right)}{\left(\gamma_{DA(Ni+0.5)} - \gamma_{DA(Ni)}\right)} \times 0.5 + Ni$$

where, γ_{DA} is the target shear strain double amplitude, which in this study is 2.0%, $\gamma_{DA(Ni)}$ and $\gamma_{DA(Ni+0.5)}$ are the shear strain double amplitude measured during the loading cycle just before and half cycle after the target of shear strain double amplitude, and Ni is the number of cycle to liquefy just before the target of shear strain amplitude reached.

Instead of using saturated specimen, liquefaction test in stacked-rings shear apparatus was conducted by using dry specimens in constant volume test. It is based on the assumption that the decrease in applied vertical stress (σ_v) during shearing in constant volume test is equal to the increase in shear-induced pore water pressure (u) that would occur in an undrained saturated test. Bjerrum and Landva (1966) proposed this assumption for DSS test (Direct Simple Shear) while Finn and Vaid (1977) confirmed it later for both triaxial and DSS tests.

TEST RESULTS AND DISCUSSION

In order to investigate the effects of pre-shearing history on the behavior of re-liquefied sand, loose and dense specimens were sheared under different pre-fixed shear strain double amplitudes ($\gamma_{DA(max)}$) of 2.0%, 3.0%, 4.0%, 5.0%, 7.0% and 10.0%.

Figure 4 shows typical results of a re-liquefaction test. In each stage, the changes in number of cycle needed to liquefy and the changes in specimen's density were evaluated. The results on re-liquefaction tests for both loose and dense sand will be discussed in detail as follows:

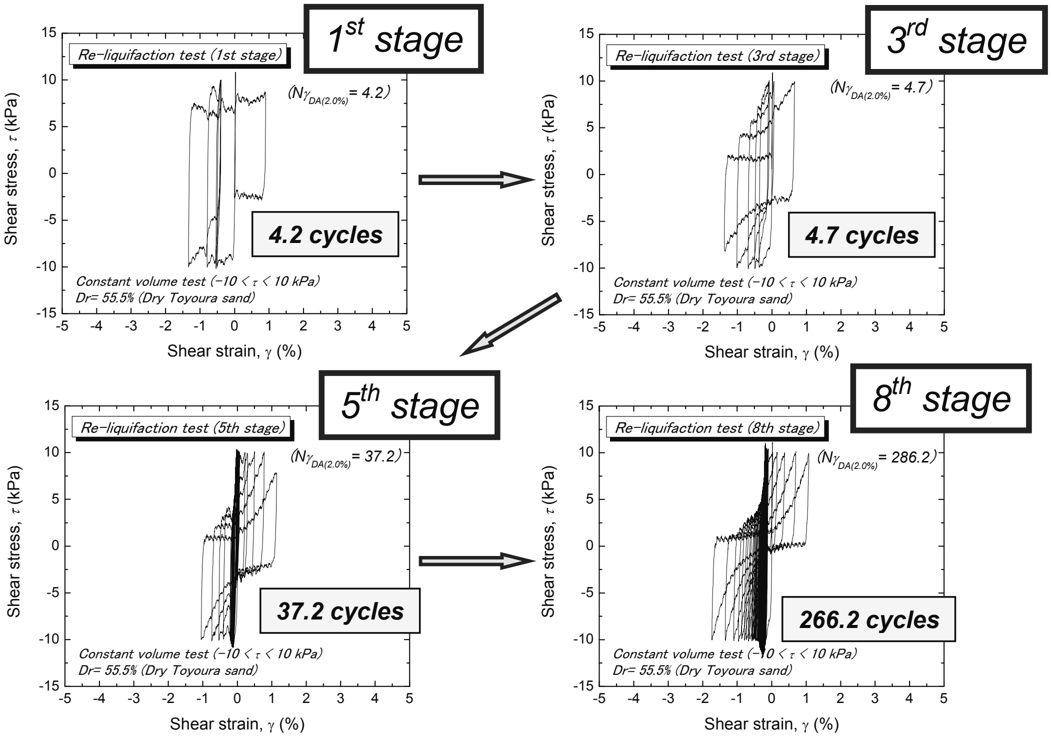

Fig. 4: Typical results of repeated liquefaction test in one sample
(stage 2, 4, 6, and 7 in this figure are skipped)

Repeated liquefaction behavior of loose sand

Four tests having similar initial relative density of about Dr_0= 55.0% (e_0=0.793) were sheared with different maximum shear strain double amplitudes ($\gamma_{DA(max.)}$) of 2.0%, 4.0%, 7.0% and 10.0%, respectively. Each of them was subjected to the cyclic shear stress ($\tau_{cy.}$) of ±10 kPa.

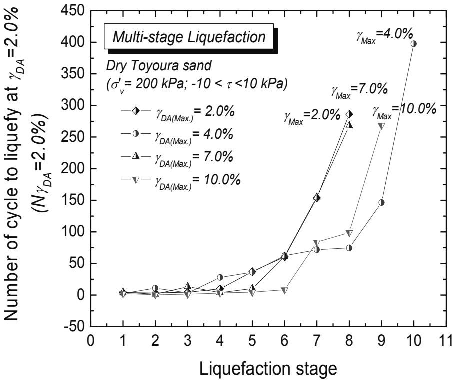

Fig. 5(a): Liquefaction resistance and liquefaction stage relationship on loose sand

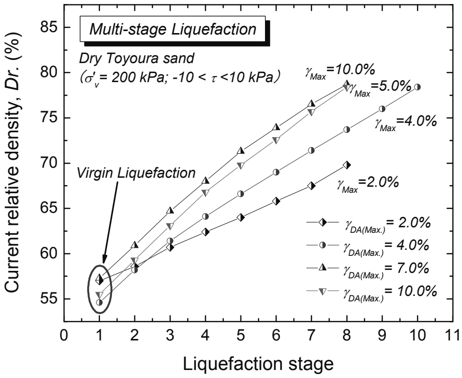

Fig. 5(b): Change in relative density and liquefaction stage relationship on loose sand

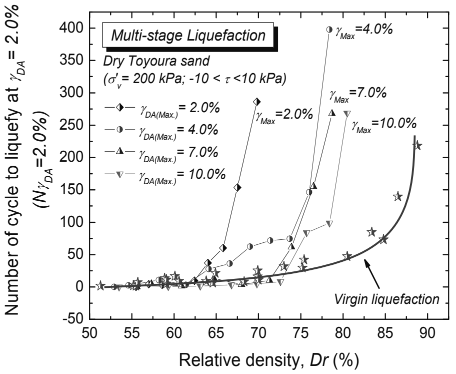

Fig. 6(a): Liquefaction resistance and relative density relationship on loose sand

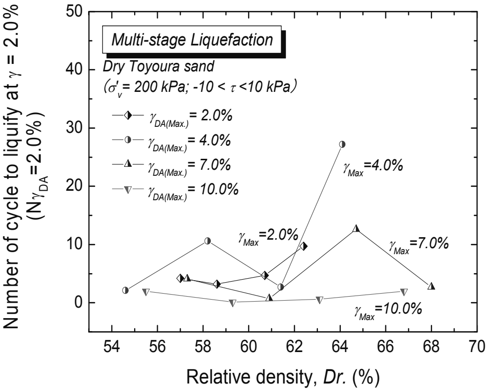

Fig. 6(b): Liquefaction resistance and relative density relationship on loose sand in early stages

Figure 5(a) shows the relationship between the number of cycle to liquefy and the liquefaction stage of loose sand. This figure indicates no significant increase in the re-liquefaction resistance of sand at least up to 5th stage in all tests. However, the re-liquefaction resistances started to increase exponentially from the 6th stage up to the last one. Figure 5(b) shows the relationship between the change in specimen's relative density and liquefaction stage. All specimens showed almost linear increase in their relative densities in each of the liquefaction stages due to re-consolidation process in post-liquefaction. It can be noticed that the larger the shear strain applied, the larger the increase of the specimen's relative density. By combining the results in Fig. 5(a) and 5(b), the relationship between number of cycle to liquefy and the change in specimen's relative density is plotted in Fig. 6(a). This figure clearly shows that the increase of the specimen's relative density did not directly translate to the increase of re-liquefaction resistance during early liquefaction stages. However, the liquefaction resistance did start to increase exponentially when the liquefaction stage continued further. It can be noticed that, the larger the shear strain applied, the weaker the soil resistance against re-liquefaction.

This observation is in contrast with the afore-mentioned observation that specimens sheared with larger shear strains gained larger increase in their densities. Therefore, this may suggest that other factors could play more important role than the increase of the density alone in determining soil resistance against re-liquefaction.

In order to compare more in detail the re-liquefaction resistances in the early liquefaction stages, their change is shown in Fig. 6(b). From this figure, it can be seen that there was no unique correlation between the re-liquefaction resistance and the specimen's relative density in the early liquefaction stages. Except the test sheared with 4% shear strain double amplitude, all tests showed the 2nd stage is the weakest stage against re-liquefaction.

Figure 6(a) also shows the comparison between the liquefaction resistance of re-liquefied soils and reference soils that liquefied for the first time. It can be seen that in the latter stages, the resistance of the re-liquefied soils were always larger than the reference ones. This may suggest that pre-shearing history also contributes to the increase in the resistance of re-liquefied soils except for the early liquefaction stages.

Repeated liquefaction behavior of dense sand

In order to verify the behaviors found earlier in the loose specimen tests, a series of test on dense specimens having initial relative densities of about Dr_0= 80% (e_0=0.702) were conducted. Six specimens were sheared under different maximum shear strain double amplitudes ($\gamma_{DA(max.)}$) of 2.0%, 3.0%, 4.0%, 5.0% (2 tests) and 10.0%, respectively. Each of them was subjected to the cyclic shear stress ($\tau_{cy.}$) of ±20 kPa.

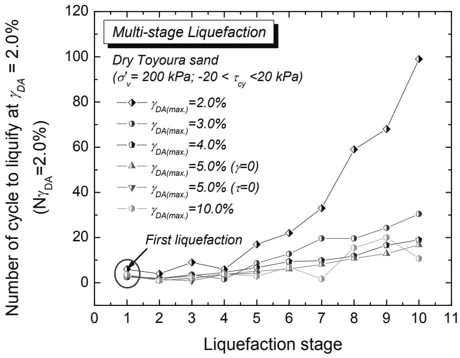

Fig. 7(a): Liquefaction resistance and liquefaction stage relationship on dense sand

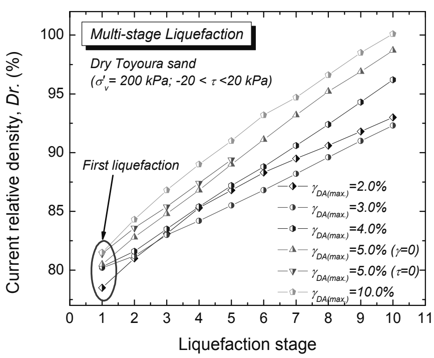

Fig. 7(b): Change in relative density and liquefaction stage relationship on dense sand

Figure 7(a) shows the relationship between number of cycle to liquefy and the liquefaction stage. Significant increase in the re-liquefaction resistance can be found only in the specimen sheared with lowest shear strain double amplitude of 2.0%, while others showed minor increase in their resistances. Figure 7(b) shows the relationship between the changes in specimen's relative density and the liquefaction stage. Need to be noted that there were slight variations of about ±2.0% in the initial relative density among different specimens. However, the behaviors shown in dense specimen tests were similar with the ones in loose specimen tests, in which specimens sheared with larger shear strain showed larger increase in their relative densities. Figure 8(a) shows the relationship between number of cycle to liquefy and the changes in specimen's relative density. It can be seen that the specimen sheared with the lowest shear strain double amplitude of 2.0% showed the strongest response, and subsequently followed by specimens sheared at 3.0%, 4.0%, 5.0% and 10.0%. These patterns also confirm the previous results which were found in the loose specimen tests. In the early stages, the irregular behavior that previously appeared in the loose specimen tests was also found in the dense specimen tests as shown in Fig. 8(b). Similarly, it was found that the 2nd stage of liquefaction test exhibited the smallest soil resistance against re-liquefaction in all tests.

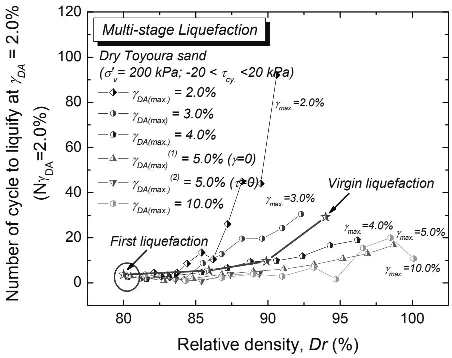

Fig. 8(a): Liquefaction resistance and relative density relationship on dense sand

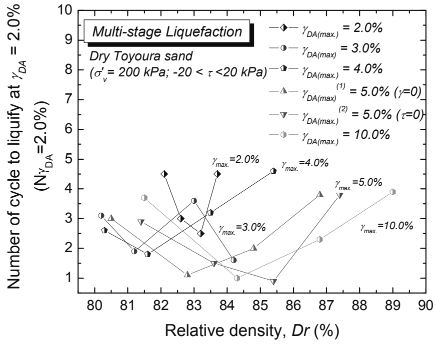

Fig. 8(b): Liquefaction resistance and relative density relationship on dense sand in the few early stages

Figure 8(a) also shows the comparison between the resistance of re-liquefied soils and the reference soils that are liquefied for the first time. Unlike the property of a loose sand in which the resistance of re-liquefied soils is always higher than the reference ones, the results from dense sand might suggest it may not be always the case. After 10 stages of re-liquefaction, specimens sheared with the shear strain double amplitudes of 4.0% to 10.0% showed weaker responses than the reference soils. Under that condition, the re-liquefied soil could be more vulnerable than the soil which liquefied for the first time. However, it is expected that soil re-liquefaction resistance will increase exponentially when re-liquefaction stage continues further.

Both findings in loose and dense specimen tests appeared to be consistent to each other. It emphasizes the significance of pre-shearing history on the re-liquefaction resistance of soil. The larger the pre-shearing deformation history applied during previous liquefaction, the weaker the soil response against re-liquefaction. These behaviors possibly appear because larger deformation means greater changes in soil particle structure. It may also affect the re-liquefaction resistance during early stages in both loose and dense specimen tests as shown in Figs. 6(b) and 8(b). During these early stages, it was found that there was no unique correlation between the re-liquefaction resistance and the specimen's density. The change on soil particle structure seems to become the predominant factor than the increase of soil's density in determining the re-liquefaction resistance of sand. It was also found that the 2nd re-liquefaction stage exhibited the smallest soil response in almost all tests. However, it is expected when the specimens becomes denser and denser in the further stages, the soil resistance against re-liquefaction will become larger.

CONCLUSIONS

The investigation on the effects of pre-shearing history in the re-liquefaction behavior of sand revealed several observations, which are:

1. Tests on loose and dense sand show re-liquefaction resistance of sand significantly affected by the pre-shearing history. The larger the shear strain history applied, the weaker the soil resistance against re-liquefaction.

2. Inconsistent patterns on the re-liquefaction resistance of sand during several of early stages (e.g 1-4 stages) may imply that the increase of density alone is not the primary factor in determining the soil resistance against re-liquefaction, perhaps the changes in soil structure plays more important role.
3. However, it is expected that as liquefaction stage goes further, the liquefaction resistance will increase exponentially. The density of soil becomes more predominant factor than others.

REFERENCES

Bjerrum, L. and Landva, A. (1966): “Direct simple shear tests on a Norwegian quick clay.” *Geotechnique*, 16(1), pp. 1-20.

Finn, W. D. L., Bransby, P. L., and Pickering, D. J. (1970): “Effects of strain history on liquefaction of sand.” *Journal of Soil Mechanics and Foundation Division, ASCE*, Vol. 96, SM6, pp. 1917 – 1933.

Finn, W. D. L. and Vaid, Y. P. (1977): “Liquefaction potential from drained constant volume cyclic simple shear test.” *Proc. of the 6th World Conference on Earthquake Engineering, New Delhi, India*

Ishihara, K. and Okada, S. (1982): “Effects of large pre-shearing on cyclic behavior of sand.” *Soils and Foundations*, 22(3), pp. 109 – 125.

Ishihara, K. and Okada, S. (1982): “Effects of stress history on cyclic behavior of sand.” *Soils and Foundations*, 18(4), pp. 31 – 45.

Ishihara, K., Iwamoto, S., Yasuda, S., and Takatsu, H. (1977): “Liquefaction of anisotropically consolidated sand.” In *Proc., 9th Int. Conf. on Soil Mechanics and Foundation Engineering*, 2, pp. 261-264. JSSMFE.

Ishihara, K. and Yoshimine, M. (1992): “Ëvaluation of settlement in sand deposits following liquefaction during earthquakes.” *Soils and Foundations*, 32(1), pp. 173 – 188.

Seed, H. B., Mori, K. and Chan, C. K. (1977): ”Influence of seismic history on liquefaction sands.” *Journal of Geotechnical Engineering Divisions ASCE*, 103, pp. 257 – 270.

Sento, N., Kazama, M., Uzuoka, R., Matsuya, A. and Ishimaru, M.(2004): “Liquefaction-induced volumetric change during re-consolidation of sandy soil subjected to undrained cyclic loading histories.” *Cyclic Behavior of Soils and Liquefaction Phenomena,* pp. 199-206, Triantafyllidis (ed.).

Towhata, I. and Ishihara, K. (1985): “Undrained strength of sand undergoing cyclic rotation of principal stress axes.” *Soils and Foundations*, 25(2), pp. 135 – 147.

Wakamatsu, K. (2000): “Liquefaction history from 416 – 1997 in Japan.” *Proc. of 12th WCEE*, CD-ROM, No. 2270 1-8.

Wakamatsu, K. (2012): “Recurrent liquefaction induced by the 2011 Great East Japan Earthquake compared with the 1987 earthquake.” *Proc. of Intl. Symp. on Engineering Lessons Learned from the 2011 Great East Japan Earthquake*, pp. 675 – 686.

Yamada, S., Takamori, T., and Sato, K. (2010): “Effects on reliquefaction resistance produced by changes in anisotropy during liquefaction.” *Soils and Foundations*, 50(1), pp. 9-25.