論文の内容の要旨
Thesis Summary

論 文 題 目 : Cyclic simple shear tests using stacked-rings on multiple liquefaction properties of sands

（砂の複数回液状化特性に関する積層リングを用いた繰返し単純せん断試験）

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This thesis is aimed to investigate the behaviors of sand subjected with multiple liquefactions and factors that have significant influence in determining its behaviors.

Liquefaction is a phenomenon in which the soil loses its strength and stiffnessand becomes more like a liquid. Liquefaction usually occurs whensaturated sand is subjected to rapid cyclic shear loading such as earthquake. Similar to the liquefaction phenomenon, multiple-liquefactionphenomenon means liquefaction that occurred repeatedly overtime at the same site.

Multiple-liquefaction phenomenon re-gained much attention after the recent Great East Japan Earthquake in Japan and Christchurch Earthquake in New Zealand. Both of these earthquakes happened almost at the same period in 2011. Recently, it was reported that at least90 cases of repeated liquefaction happened during the Great East Japan Earthquake alone.

Researchers found that the majority of the cases mentioned before happened in the three typical types of area, which are former/abandoned river channel, artificial fills, and lower slopes of sand dunes. Based on these recent cases, it is clear that not just liquefaction certainly is able to re-occur at the same site, but also the damage caused by the following liquefactions could be more severe than the previous one.

Several pioneer works have been conducted by investigating the behaviors of sand during 2-stage of liquefaction (re-liquefaction). It was found that the liquefaction resistance of soil is very much affected by at least two major factors,which are the effects of strain amplitude and anisotropy.

Most of the previous studies done by previous researchers were only capable to simulate at most 2-stage of liquefaction test. This was due to the limitation of the apparatuses itself (e.g. triaxial and torsional shear apparatuses). These types of apparatus are not suitablefor performing multi-stage liquefaction test, since the flexible membrane is not capable of maintaining the geometry of the specimen after full liquefaction or under extremely large shear deformation. To overcome these problems, Institute of Industrial Science – The University of Tokyohas developed a new apparatus, so called stacked-ring shear apparatus. This apparatus was purposely designed to be able to maintain the geometry of the specimen to remain constant under multiple liquefactions or large shear deformation.

Despite its advantage, the stacked-ring shear apparatus has a major drawback. Large excessive friction is generated between the soil particles and the ring itself. The development of the apparatus is needed to reduce the amount of excessive friction. In general, two attempts were conducted: first was to reduce the contact surface of the specimen by reducing the number of rings composing stacked rings, second was to layer the surface of the rings using frictionless material (Diamond-Like-Coating).

In general, there are two types of test that were conducted in the current study. Type-I test is conducted to perform multi-stage liquefaction test where no residual deformation is allowed during each liquefaction stage ($\gamma = 0$), while the type-II test is conducted to performmulti-stage liquefaction test, where some form of residual deformation is allowed ($\gamma \neq 0$). The former test is aimed to investigate the effects of shear strain amplitude, while the latter test is aimed to investigate the effect of stress-induced anisotropy caused by residual strain.

The procedures to conduct both types of test in the stacked-ring shear apparatus are almost similar. First, the specimen was consolidated one dimensionally up to the pre-determined initial confining stress. Then, each specimen is sheared cyclically under constant volume condition up to the maximum pre-fixed value on each liquefaction stage (e.g. γ_{DA}= 2.0%, 5.0%, 10.0%, and etc.). For the type-I test, another half-cycle of cyclic shear loading needs to be appliedafter reaching its maximum pre-fixedvalueto the origin (γ= 0%). This is done in order to avoid/minimize the effects of induced-anisotropy on the liquefied specimen. For the type-II test, the shear loading is stopped at zero shear stress (τ= 0 kPa) after it reach the maximum pre-fixed shear strain amplitude value. The next liquefaction stages are done by following the same procedures as has been described earlier in the first and second stages.

The results on the both types of test revealed that the effects of increase in the specimen’s density during re-consolidation in post liquefaction arenot significant in determining the soil resistance against multiple liquefactions. The specimen which underwent largershear deformation shows larger increase in its density, but smaller liquefaction resistance in the following liquefactions. In the other hand, the specimen which underwent smaller shear deformation showssmaller increase in its density, butlarger increase in its liquefaction resistance in the following liquefactions.

The results of the type-I test revealed that the soil behaviors during multiple liquefactions are very much affected with the history of strain amplitudes. The specimens sheared with larger strain amplitude showedsmaller resistance against multiple liquefactions. In the other hand, the specimens sheared with smaller strain amplitude showed larger resistance against multiple liquefactions. However, these may not show the complete impact of the strain amplitude to the soil behaviors during multiple liquefactions.

These experimental data may not enough to understand the impact of different stain amplitude to the soil behaviors subjected with multiple liquefactions. An additional observation is conducted with the aim to investigate the local deformation behaviors of the specimen during multiple liquefactions by using image analysis method.

To conduct the image analysis, a digital camera was installed to capture the movement of each ring with certain interval of time. Then, the series of picture were analyzed to obtain the deformation of each ring.

Image analysis results found that the specimens which hadundergone large shear deformation havelarger variations on their local shear deformations. Some sections of the specimen showed larger shear deformations, while other sections showed smaller shear deformations as compare to their global one. The sections that were sheared larger than others may create localization within the specimen itself.Consequently, the localized specimen would have lower resistance in the future liquefactions.

Both results from experimental data and image analysis are very important to understand the mechanism that is taking place during multiple liquefactions. One of the methods to identify this mechanism is using energy approach. The energy approach is based on Newtonian energy concept. In soil mechanics, the energy is mainly consumed through the rolling and sliding mechanisms. These two modes of mechanism directly related to the increase or the decrease of soil's effective stress (σ') during liquefaction. The energy approach shows relation between the dissipated energy in a stage of liquefaction ($\Sigma\Delta W$) to the soil resistance in the future liquefaction.

The results found that there is a virtual boundary in which the amount of dissipated energy will result on increasing or decreasing the liquefaction resistances of the future liquefaction. The amount of energy dissipated in a stage of liquefaction will have a positive impact ($\Sigma\Delta W^{(+)}$) when the stress path of the sheared specimendoes not passing the phase transformation line (PTL). Within this boundary, the larger the dissipated energy is, the higher the liquefaction resistance will be in the future liquefaction. If the applied energy of the sheared specimen exceeds the PTL, a negative impact is started to take place ($\Sigma\Delta W^{(-)}$). In this region, the larger the dissipated energy is, the lower the liquefaction resistanceswill be in the future liquefaction.

As important to the effects of strain amplitude, the effects of anisotropy (type-II test) also showed significant impact in determining the soil behaviors during multiple liquefactions.

The effects of stress-induced anisotropy are investigated by analyzing the dilatancy characteristics of the specimen that had experienced a single or multiple liquefactions before.Then, the liquefied specimen is re-consolidated to its original effective stress and subjected with drained cyclic shear constant stress test to obtain their dilatancy characteristics. In an isotropic specimen, the dilatancy characteristics are symmetric in each direction of loading.

The results found that the specimen affected by anisotropy has unsymmetrical dilatancy characteristics on different loading directions (e.g. clockwise and anticlockwise). Moreover, the specimen that affected by anisotropy shows higher contraction than the specimen that does not. These behaviors mean thatthe specimen affected by stress-induced anisotropy would have smaller liquefaction resistance than the specimen that does not affected by anisotropy.