論文の内容の要旨
Thesis Summary

論文題目: Local Deformation and Repeated Liquefaction Properties of Segregated Sand Specimen in Hollow Cylindrical Torsional Shear Tests

（分級した砂供試体の中空ねじりせん断試験における局所変形および繰返し液状化特性）

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Liquefaction causes large deformation of ground consisting of sandy soils. Damage caused by liquefaction is so vast that repairing of structures on liquefied ground is difficult and costly. In most of past large earthquakes, liquefaction took place in reclaimed lands constructed by dredging and pumping method. Dredging in this dissertation is defined as removal of materials from the bottom of rivers or sea. The materials removed during dredging are pumped in to form reclaimed land. Under this condition, there is no soil densification performed and soil particles sediment due to gravity. This method would clearly result in segregation because of the fine particles lagging behind due to their smaller sedimentation velocities through water so that soil deposit may not be uniform.

Numerous researches have reported that the strength and deformation of sands can be remarkably influenced by methods of specimen preparation. Most prior studies have focused their efforts to establish a standard method of specimen preparation by which homogenous specimens can be formed in order to obtain reliable and repeatable results. However, these techniques may not be valid in all situations, especially when dealing with sandy soil that is deposited in-situ using the dredging and pumping method. Past relevant studies based on model tests, soil element tests and site investigations reported that the effect of soil layering on the emergence of water film, or in water interlayer term at the interface between the top of the saturated sand strata and the base of a layer of low-permeability fines during liquefaction. Many researchers also reported the emergence of water film in shaking table and dynamic centrifuge tests. This water film may play an important role in post-earthquake large lateral flow in liquefied ground.

Re-liquefaction is another important topic in this study. During the March 2011 Great East Japan Earthquake Disaster, there are a lot of evidences that sand deposits can liquefy repeatedly (or "re-liquefaction") at the same sites after initial liquefaction during previous earthquake shaking. It is reported that re-liquefaction is observed at a total of 62 sites in the Kanto region (35 sites are reclaimed land), where past liquefaction occurred during the 1987 Chibaken Toho-oki Earthquake (M_w 6.7). Re-liquefaction is also reported during September 2010 (M_w 7.1), February 2011 (M_w 6.2) and June 2011 (M_w 6.2) Canterbury Earthquakes. Many studies have concluded that liquefaction resistance may increase with the increase of relative density. However, there are a lot of evidences that liquefaction can take place repeatedly in natural deposits and reclaimed lands. It is found that sand deposits which had been liquefied, might be re-liquefied by a future earthquake even with smaller amplitude than the previous one. In other words, the liquefaction resistance can decrease after first liquefaction.

A disturbed sand sample for experiment is retrieved from a reclaimed area in Katori city, which is located near Tone River. All tests in this experimental program are performed on this sand with cut-off diameter of 4.75 mm, mean grain size (D_{50}) = 0.16 mm, coefficient of uniformity = 1.81, coefficient of gradation = 0.97, specific gravity (G_s) = 2.65, maximum void ratio = 1.35, minimum void ratio = 0.92, and fines content of about 5%. Specimens are reconstituted using two different techniques: water sedimentation and moist tamping. The water sedimentation specimen is prepared initially by filling the acrylic pipe with de-aired water. The height of water is 50 cm from the bottom. A mixture of soil and water at a mass ratio of 1:2 is poured into the acrylic pipe using a funnel. By repeating these procedures three times, a segregated specimen is prepared, where the top part of silt layer in the third layer is cut so that the specimen consists of three sand layers and two silt layers. For comparison purpose, the moist tamping method is used to reconstitute uniform specimen

Torsional shear tests are conducted on hollow cylindrical specimens having an initial height of 30 cm, inner and outer diameters of 12 cm and 20 cm, respectively. Double vacuum method is used during the saturation process, considering the large specimen size. As a result, Skempton's B-values could be achieved to be greater than 0.96 in all the specimens. After completion of saturation, the specimens are consolidated isotropically to effective stress, σ_c' = 100 kPa with relative density after consolidation, Dr_c = 26-28%. Permeability tests are conducted after isotropic consolidation at each stage before the liquefaction test. Then, undrained cyclic loadings are applied with constant shear strain rate of 1%/min with single amplitude shear stress of 10 kPa, 12 kPa, 15 kPa, and 20 kPa while maintaining the specimen height constant. The first loading direction is in the clockwise direction which will be hereafter defined to be positive. The specimens are considered to have been liquefied when the double amplitude of shear strain, γ_{DA}, reached 15%. At the end of liquefaction test, the global shear strain (γ_G) is resumed to be zero in some cases and the shear stress (τ) is resumed to be zero in other cases while maintaining the undrained condition. By opening the drainage valve, the specimen is re-consolidated into the same initial effective stress, $\sigma c'$ = 100 kPa. The next stages of liquefaction tests are conducted by following the same procedures as those followed in the first liquefaction test.

A special image analysis technique is developed to improve local deformation measurement of sand specimen in hollow cylindrical torsional shear test. This technique involves the use of a latex membrane with dots marked in a grid pattern with approximately 5 mm spacing. Images of these dots are recorded using a digital camera with the resolution of 7360x4912 pixels that synchronously shoots the membrane surface at desired time intervals. LED light strips are employed to improve low lighting condition and to avoid reflection or shadow. Movements of these dots are tracked in terms of their center of mass using an image processing software with the accuracy of about 0.01 mm. The corrections of coordinates are applied to the data obtained from digital images to evaluate the dot positions on the curved specimen surface.

Based on the test results, the newly introduced procedure of segregated specimen preparation to model reclaimed land constructed by dredging and pumping method in hollow cylindrical torsional shear tests could be validated. Based on permeability test results, coefficients of permeability of the sand layer, the fines layer, and the segregated specimens were obtained as 1.68 x 10^{-3} cm/s, 2.66 x 10^{-5} cm/s, and 2.59 x 10^{-5} cm/s, respectively, ensuring that the permeability of the sand layer is much higher than that of the fines layer.

The installation of many LED lights that were located outside of the pressure chamber could improve the accuracy in observing the movements of the dots on the membrane. In addition, the newly proposed coordinate correction procedure by involving a ninth order polynomial equation could be applied with higher accuracy.

The specimens prepared by water sedimentation and moist tamping at the same relative density after isotropic consolidation showed significantly different behavior from each other. During undrained cyclic loading test, the water sedimentation specimens showed higher liquefaction resistance than the moist tamping specimens. During undrained monotonic loading, the water sedimentation specimens showed more dilative behavior than the moist tamping specimens. These different behaviors were possibly caused by different fabrics and soil particle structures between the water sedimentation specimens and the moist tamping ones. In the moist tamping case, particles are packed more uniformly with fines particles that scatter in between sand particles. However, in the water sedimentation case, particles are packed in a non-uniform manner exhibiting a graded bedding structure, where the fines particles are located on the top of the sand particles.

Under the test conditions employed in this study, formation of the water film could not be observed during the undrained cyclic loading test, though several attempts were made to observe it by using a partially-reinforced membrane and employing silicone treatment to reduce the effect of local membrane penetration, by increasing the loading speed, and by increasing the fines content. Instead, it could be observed that local drainage, wrinkling of membrane, and pore water migration occurred during undrained loading. The occurrence of pore water migration was consistent with the vertical expansion of the fines layers that was observed by using image analysis.

The relative density of the specimen was found to increase gradually due to the effects of reconsolidation after liquefaction. However, the liquefaction resistance in the next stage could not be uniquely correlated with the relative density. In some cases, the liquefaction resistance was decreased at second stage. It was also found that the liquefaction resistance of the water sedimentation specimen is mostly controlled by the properties of the sand layers, suggesting that the fines layers in the reclaimed ground would affect the overall liquefaction resistance to limited extents. On the other hand, it could be confirmed with the water sedimentation specimen that the residual strain in the post liquefaction process has significant impact on the liquefaction resistance in the next stage. In most of the tests on specimens without residual strain, the re-liquefaction resistance increased with the liquefaction stage. In contrast, the specimens with non-zero residual strain exhibited much lower re-liquefaction resistance than the specimens without residual strain under otherwise the same test conditions.

It could be also confirmed that, even with the water sedimentation specimen, application of small cyclic drained pre-shearing could increase significantly the liquefaction resistance in the next stage with limited increase of the relative density. However, such improvement effect was found to decrease largely, once the specimen underwent a severe liquefaction history.