論文の内容の要旨

Thesis Summary

Direct and indirect local deformation measurements of sand specimen in undrained cyclic triaxial and torsional shear tests
(非排水繰返し三軸・ねじりせん断試験における砂供試体の局所変形挙動の直接・間接的計測)

趙闖

Liquefaction is always accompanied by the increasing of pore water pressure, that is, one of the most important reasons for losing strength and ground sediment during earthquakes. In the recent two earthquakes, extensive liquefactions occurred in loose deposit. For example, liquefactions took place over a wide range area of the reclaimed lands along Tokyo bay area in 2011Tohoku earthquake. Based on reconnaissance project, more than 184 liquefaction sites were found in total. There are two main problems confronting researchers when dealing with a situation where liquefaction takes place. One is the condition of specimen required to trigger liquefaction, the other is the evaluation of potential deformations during and after liquefaction.

The loose deposits formed by hydraulic filling (dredging and pumping) and natural deposits near rivers have large potential to liquefy during seismic event. Related researches have been conducted in recent decades. The complicated geology indicates that there are some less permeable layers intercepting the stratum. This may be affected by the sediment of sand particles through water with different velocities, which is determined by the particle size. This segregation phenomenon will have a significant affection on the liquefaction stabilities of layered deposits. Past relevant studies based on shaking table tests, centrifuge tests and model tests indicated that water film underneath the less permeable layer was generated during shaking. The water film lasted for a while after the cease of shaking. Moreover, the existence of water film decreased the stability of slope in the model test. The generation of water film resulted in lateral displacement of liquefied ground.

The deformation of sand specimen in laboratory tests, such as triaxial tests, torsional shear tests and plane strain compression tests, maybe not uniform, in particular

on heterogeneous specimen. Therefore, the deformations measured at the boundaries of specimen could not be valid parameters to present the behaviors of soil. In drained element tests, local deformation has been widely investigated by continuously updated techniques such as image analysis, Particle Image Velocimetry, Digital Correlation, photogrammetry and X-ray and so on. However, since the deformations along the specimen are always assumed to be uniform during testing, little attention has been paid on the local deformations of sand specimen in undrained element test. Some researchers also supposed that strain localization would not occur in the liquefaction tests. Up to now, there is discrepancy between researchers when dealing with strain localization in undrained element test. It is urgent to conduct researches on local deformation of sand specimen in undrained test. Further, the mechanism of water film generation on heterogeneous specimen in liquefaction test could be studied to some extent.

Toyoura sand specimen specked by blue colored Silica sand was employed in undrained triaxial test to investigate the local deformations directly and indirectly by image analysis method. In order to increase the color contrast for image analysis, Toyoura sand specimen was replaced by mixed white and black colored Silica sand at a mass ratio of 10 to 1. The Silica sand specimen was speckled by black colored Silica sand, with a diameter of 75 mm and a height of 150 mm. These two colored Silica sand had the same physical properties, with a mean particle size of 0.52 mm, a uniformity coefficient of 2.0, a gradation coefficient of 0.92 and a specific gravity of 2.633. The maximum and minimum void ratios of mixed sand were 1.047 and 0.688, respectively. Both air pluviation and moist tamping methods were applied to prepare the sand specimens in triaxial liquefaction test. The mixed Silica sand specimens were also used in the undrained hollow cylindrical torsional shear tests, with an outer diameter of 200 mm, inner diameter of 120 mm and a height of 300 mm. Only air pluviation method was used to make uniform sand specimens in undrained torsional shear tests. In addition, a disturbed sand named as Katori sand from reclaimed area was used to prepare segregated sand specimens. Only water sediment method was applied to prepare the segregated specimens.

For all the undrained triaxial and torsional shear tests, the double vacuuming method was used to obtain a B value larger than 0.96. After saturation, the specimen was consolidated to an effective confining stress of 100 kPa. Undrained cyclic axial loading with a constant single amplitude of deviator stress was applied. The relative density and amplitude of deviator stress were changed in different undrained triaxial liquefaction tests. On the other hand, undrained cyclic torsional loading with a constant single amplitude of shear stress was implemented in the torsional shear test while the vertical displacement was not allowed.

In addition, image analysis was applied in these tests for capturing the local deformations of sand specimen through a transparent membrane. Black latex dots were pasted on the surface of membrane by perfect grids with 5 mm intervals on horizontal and vertical directions. LED lights were added to increase the brightness of specimen surface. The side view of specimen was recorded by using a digital camera in front of cell with a prescribed time interval. The coordinates of dots on membrane and sand particles patterns were obtained respectively by a software named Move-Tr2D.

Since the rays were refracted twice by two interfaces among three mediums, the image was distorted largely, especially at the boundary areas of image. No coordinate correction was considered in the triaxial liquefaction tests. A coordinate correction procedure was developed in torsional shear tests to eliminate the distortion effects. Theoretical analysis and calibration tests were employed to verify the validity of proposed coordinate correction method. The resolutions of current image analysis are around 0.025 mm/pixel in triaxial test and 0.05mm/pixel in torsional shear test, respectively. In the calibration test, the calculation errors of two neighboring dots were less than 0.2 mm on horizontal and vertical directions even when the rotation displacement was larger than 46 mm. The effects from lens, curvature of cell and specimen and refractions had been taken into consideration in the proposed coordinate correction method. The local strains of each grid at specimen surface were computed and finally plotted by local strain distributions, by which the local deformations of specimen could be displayed visually and clearly.

Based on the direct and indirect evaluations of local deformations of sand specimen in triaxial liquefaction tests, the relative displacements between dots on membrane and sand particles named slippage would not be zero and could not remain constant along cyclic loading. The vertical slippage had a significant leap when excess pore water pressure reached 1.0 at each time during cyclic mobility, which indicated that sand particles sunk during liquefaction. Regardless of air pluviation and moist tamping sample preparation methods, vertical slippage always occurred. Moreover, necking phenomenon of specimen prepared by moist tamping was found at small axial strains. From local strain distributions, the local strains of specimen prepared by air pluviation method were more uniform than the local strains of specimen prepared by moist tamping method.

Similarly, vertical slippage also occurred when excess pore water pressure reached 1.0 in undrained torsional shear tests. In addition, there was no slippage before initial liquefaction. Therefore, the local deformation results from indirect evaluation (from dots on membrane) could represent those from direction evaluation (sand particles) before initial liquefaction. Horizontal slippage existed throughout the test and varied with the cyclic shearing under a limited value. There was almost no vertical slippage when relative density of Silica sand specimen was larger than 60%, which meant the potential of vertical slippage would decrease due to a smaller void ratio of specimen. There was another factor affected the quantity of vertical slippage which was the accumulated movement of the measured point. The vertical slippage would be small when loose specimen was sheared under a relative large shear stress by which the specimen reached

15% double amplitude of shear strain with little shear movement. Meanwhile, the condition of excess pore water pressure determined when the vertical slippage would happen during liquefaction tests.

Segregated sand specimen in torsional shear test induced different increments of excess pore water pressure at two sides of less permeable layer. Through image analysis results and original photos taken during the tests, relatively large local strains were observed near the less permeable layer. The thickness of fine layer had a significant affection on the concentration of pore water beneath the fine layer. The difference of pore water pressures between bottom and top of specimen, which was intercepted by fine layers, increased with the absolute value of shear stress. Near the status of initial liquefaction, this variation rule of differential pore pressure changed and the maximum value of the differential pore pressure was obtained when the initial liquefaction occurred. Under such circumstance, the largest potential to form water films was generated. A local water film was found at the interface between sand layer and above fine layer when the initial liquefaction was reached. However, these water films were generated in membrane wrinkles where the sand might be looser than other positions outside of wrinkles. The migration of pore water from the bottom of specimen to the upper part created the generation condition of water film. Based on the results from image analysis, large local strains at fine layer were observed both from the direct and indirect evaluations of local deformations. Since the stiffness of fine layer was smaller than the sand layer during consolidation, serious membrane penetration was observed at the fine layer by the local strain distributions. Interestingly, due to pore water concentration at fine layer, the effect of membrane penetration disappeared gradually and shear strain localization was observed at the interface between fine layer and sand layer.