論文の内容の要旨

論文題目
Deformation Characteristics of Sand Subjected to Cyclic Drained and Undrained Torsional Loadings and Their Modelling
(排水・非排水繰り返しねじりせん断時の砂の変形特性とそのモデル化)

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The ultimate objective of the current study is to propose a model to simulate the drained and undrained cyclic torsional shear behavior of sand. One promising framework for modeling undrained behavior of soil is to relate the elastic volume change increment, which comes from consolidation to plastic volume change increment, which comes from dilatancy. For this purpose, one essential requirement is to accurately evaluate the quasi-elastic deformation properties of sand and to model them appropriately in order to evaluate the overall elastic strain components and hence the plastic strain components as well. A torsional shear apparatus with hollow cylindrical specimens is a good tool to study the above, since it can reasonably reproduce the actual stress states of in-situ soils. In addition, it can be used to directly evaluate shear modulus of soils with other quasi-elastic deformation properties.

However, despite the above stated advantages, torsional shear testing on hollow cylindrical specimens is prone to several limitations such as the increased effects of end restraint and membrane penetration, system compliance problems and effects of specimen preparation method. Therefore, as the first step of the current study, it was attempted to investigate the effects of the above stated issues on deformation measurement of hollow cylindrical specimens and take necessary precautions to minimize such effects.

Since it was observed that the locally evaluated shear modulus ($G_{z\theta}$) using the recently developed Pin-typed Local Deformation Transducer (PLDT) system is about 10 - 15 % smaller than that evaluated by using externally attached proximity transducers (gap sensors), while locally and externally evaluated Young's moduli (E_z) show no such difference, a series of experiments were conducted on dry Toyoura sand (D_{50} = 0.162 mm) hollow cylindrical specimens to investigate the possible effects of end restraint on locally evaluated shear and Young's moduli. All the specimens were equipped with diagonally attached PLDTs at different elevations along a vertical line of the specimen, with external transducers. Cyclic torsional shear loadings with single strain amplitudes of 0.0015 %, 0.015 %, 0.15 %, respectively and cyclic vertical loadings with 0.001 % and 0.015 % single strain amplitudes, respectively were conducted at different confining stresses. The ratios of externally and locally evaluated equivalent shear moduli (G_{eq}) at different elevations were taken as an index for the amount of end restraint.

In addition, possible effects of system compliance problems such as bedding error, misalignment, imperfect rotation of the top cap such as a rocking movement, on the evaluation of above properties were also investigated by conducting a series of preliminary experiments on a metal dummy specimen. Effects of end restraint were avoided by allowing a 2 mm gap between the top cap and dummy specimen. PLDTs were attached around the top cap across this gap with one end on the dummy and the other end on the top cap. By assuming that the top cap is connected to a soil specimen of the same size as the dummy, the top cap was subjected to small rotational and vertical cyclic movements that corresponded to 0.0015 % and 0.015 % single strain amplitudes. Measurement of deformations from PLDTs around the top cap were compared with each other and with external measurement to identify the extent and nature of system compliance problems in the apparatus used.

Effects of two air pluviation specimen preparation techniques on the isotropy of horizontal bedding plane of hollow cylindrical sand specimens were investigated with the help of locally evaluated deformations. Seven specimens were prepared by following the conventional procedure, i.e. pluviating sand into the mould by moving the nozzle of the funnel in alternative clock-wise and counter clock-wise directions (denoted as CW & ACW). In the rest of the specimens, pluviation was done by moving the nozzle of the funnel primarily in radial direction, while moving the nozzle gradually in the alternative clock-wise and counter clock-wise directions as well (denoted as R & C). Two specimen geometries were tested in the current study to investigate the possible effects of membrane penetration and end restraint on volume change measurement. Outer diameter and the height of specimens were kept constant (20 cm and 30 cm, respectively) in all the specimens, while inner diameters are taken as 12 cm and 16 cm for the specimen sizes A and B, respectively. Size A specimens were prepared in two initial relative densities. Some specimens have initial relative densities varying from 75 % - 85 %, while others have about 50 % initial relative density. All the size B specimens have about 80 % initial relative density.

Saturated hollow cylindrical Toyoura sand specimens were subjected to isotropic loading (IC) from $\sigma'_z = \sigma'_r = \sigma'_\theta$ = 50 kPa to 400 kPa and unloaded to 100 kPa followed by large monotonic or cyclic torsional loadings (ITS). Locally evaluated vertical, circumferential and radial strains (ε_z, ε_θ, and ε_r, respectively), and volumetric strain (ε_{vol}) were compared within the specimens and among specimens to investigate the effects of two pluviation techniques on isotropy of horizontal bedding plane of the specimen. Small vertical, torsional and isotropic cyclic loadings were conducted at different stress levels to evaluate the quasi-elastic deformation properties such as Young's modulus, shear modulus, Poisson's ratios ($\nu_{z\theta}$ and ν_{zr}) and bulk modulus (K) of sand. Applicability of the recently developed IIS model in simulating quasi-elastic deformation properties and hence overall elastic strain components of sand under torsional shear was also investigated.

Generalized hyperbolic equation (GHE) was employed to simulate the monotonic stress-strain relationship (skeleton curve) of sand subjected to drained torsional shear loading. Plastic strain components were evaluated by subtracting the elastic shear strain component, which was evaluated by employing the IIS model, from total shear strain.

Then the subsequent cyclic loadings were modeled by employing the extended Masing's rules (proportional rule and drag rule). Two additional concepts were introduced into the modeling aiming at simulating large cyclic behavior close to the peak stress state. Experimental evidences suggest that the peak stress of sand slightly increase with subsequent cyclic loading (hardening). In addition, plastic shear modulus significantly decreases with large cyclic loading due to the damage to soil structure after the stress state first exceeds its phase transformation stress state. These two factors were considered in the current study respectively, when applying the extended Masing's rules in the subsequent cyclic loadings.

Modeling of stress-strain relationship as described above is not sufficient to describe the volumetric behavior of soil. Therefore, a relationship that deals with the ratio of plastic strain increments to stress ratio (stress-dilatancy relationship) is required to address this problem in addition to the stress-strain relationship. In order to accurately evaluate the stress-dilatancy relationship of sand subjected to cyclic torsional shear loading, the volume change measurement system was modified by introducing a high sensitive electronic balance by replacing the conventional low capacity differential pressure transducer (LCDPT).

Then it was attempted to simulate the volumetric strain of sand subjected to drained cyclic torsional shear loading by combining the stress-strain relationship as described above with the stress-dilatancy relationship.

Finally, a model is proposed to simulate the cyclic undrained behavior of sand. When soil is subjected to undrained loading, excess pore water pressure generates within the specimen causing change of mean effective stress (*dp'*). Therefore, volumetric strain is induced due to consolidation or swelling of specimen. On the other hand, shear stress induces another volumetric strain component due to positive or negative dilatancy. Since there should be no change in the total volume of specimen during undrained loading, it is reasonable to assume that the volume change increment due to consolidation or swelling ($d\varepsilon^{c}_{vol}$) and volume change increment due to dilatancy ($d\varepsilon^{d}_{vol}$) should be counter-balanced to each other ($d\varepsilon^{c}_{vol} = - d\varepsilon^{d}_{vol}$). It is experimentally found that the bulk moduli ($dp'/ d\varepsilon^{c}_{vol}$) can be expressed as a function of current p'.

$d\varepsilon^{d}_{vol}$ can be evaluated by combining the modeling of stress-strain relationship of drained cyclic torsional shear loading with the stress-dilatancy relationship. When evaluating $d\varepsilon^{d}_{vol}$, it is assumed that there exists a unique relationship of $(\tau_{z\theta}/p')/(\tau_{z\theta}/p')_{max}$ versus $\gamma^{P}_{z\theta}$ among drained and undrained cyclic loadings, hence the same stress-dilatancy relationship as in the case of drained loading can be employed to evaluate $d\varepsilon^{d}_{vol}$ during undrained loading. Note that the effects of over-consolidation on the stress-dilatancy relationship were also addressed in the current study.

It should be noted that, accurate determination of $(\tau_{z\theta}/p')_{max}$ for drained and undrained loading is a difficult task in dense sand. Therefore, the parameters for undrained loading were determined by slightly modifying the drained GHE parameters.

The following conclusions on the effects of end restraint and system compliance problems in the deformation measurement of hollow cylindrical specimens can be drawn from the results of the series of experiments on dry Toyoura sand specimens and metal dummy specimens.

Effects of end restraint on the evaluation of quasi-elastic Young's and shear modulus of hollow cylindrical sand specimens are not significant since the specimen seems to deform uniformly within the quasi-elastic strain range. However, effects of end restraint become significant with the increase of shear strain amplitude. In addition, it is necessary to evaluate the initial setting angle of the diagonal PLDT accurately to perform reliable shear strain measurement. Furthermore, any effects due to system compliance problems can be reduced by taking the average of the measurements from opposite sides of a diameter.

The following conclusions can be drawn from the analysis and modeling of quasi-elastic deformation properties.

Effects of bedding error on the evaluation of quasi-elastic deformation properties were found to be small. After accurately evaluating the initial setting angle of diagonal PLDT, both externally and locally evaluated Young's and shear moduli become similar to each other, respectively. Data from electronic balance can be used to evaluate the quasi-elastic bulk moduli (K) of sand, while effects of membrane penetration significantly affect its reliability. Locally evaluated K during IC by assuming the isotropy of horizontal bedding plane ($\varepsilon_{\theta} = \varepsilon_{r}$) is very similar to the K evaluated by using electronic balance data without any correction for membrane penetration in size A specimens.

IIS model can reasonably simulate the quasi-elastic deformation properties of Toyoura sand subjected to torsional shear and capable of evaluating overall elastic strain components accurately.

The series of experiments on saturated Toyoura sand specimens that were prepared by using two air pluviation techniques revealed the followings.

ε_{z} and ε_{θ} during IC are comparable to each other (ε_{z} is slightly smaller than ε_{θ}), while ε_{r} is significantly larger than either ε_{z} or ε_{θ}. This difference is much greater in size B specimens. Evaluation of ε_{r} is largely affected by the possible presence of locally loose zones near the membranes of the specimen, while ε_{θ} and ε_{z} are not affected. Therefore, the locally measured ε_{r} may not represent the average ε_{r} of the specimen. However, specimens prepared by pluviating sand in R & C method seems to improve the uniformity of specimen in radial direction, reducing the effects of locally loose zones near the membranes on the evaluation of ε_{r}. Hence, the difference between measured ε_θ and ε_r during IC is much smaller in the specimens prepared by R & C method.

Locally evaluated ε_{vol} during IC by assuming the isotropy of horizontal bedding plane ($\varepsilon_\theta= \varepsilon_r$) is very similar to the measured ε_{vol} by either LCDPT or electronic balance without any correction for membrane penetration in size A specimens. This is suggesting that the true average ε_r of the specimen is similar to ε_θ, irrespective of the specimen preparation method, although the uniformity of hollow cylindrical specimen in radial direction is affected by the air pluviation method. Measured ε_{vol} by either LCDPT or electronic balance during IC should be affected by both membrane penetration and end restraint effects. Therefore, a correction for membrane penetration only is not sufficient to obtain reliable ε_{vol} in testing of hollow cylindrical specimens. Although the initial relative densities are similar in size A and B specimens, ε_{vol} evaluated by the electronic balance in size B specimens during IC are significantly larger than that of size A specimens owing to the larger effects of membrane penetration due to increase of surface area of membranes. However, locally evaluated ε_{vol} during IC by assuming the isotropy of horizontal bedding plane ($\varepsilon_\theta = \varepsilon_r$) are very similar between both size A and B specimens.

GHE can well simulate the backbone curve of Toyoura sand subjected to drained torsional shear loading. Extended Masing's rules alone were not capable of simulating the large cyclic stress-strain relationships close to peak stress state. In addition, the hardening behavior observed in constant amplitude cyclic loading can not be well simulated either. Simulation of drained cyclic stress-strain relationship could be improved significantly, and the simulated results become consistent with the experimental data after introducing the hardening and damage factors into the extended Masing's rules.

Results from cyclic torsional shear experiment suggest that unique relationships between shear stress ratio ($\tau_{z\theta}/p'$) and dilatancy ratio ($-d\varepsilon^p_{vol}/d\gamma^p_{z\theta}$) exist for $d\gamma_{z\theta} > 0$ and $d\gamma_{z\theta} < 0$, respectively. Therefore, an empirical stress-dilatancy relationship can be proposed for cyclic torsional shear loading to simulate the volumetric behavior of sand. However, it was observed that the stress-dilatancy relationships seem to slightly shrink or expand with number of loading cycles depending on the accumulated plastic strain between current and previous turning points. In addition, the effects of over-consolidation significantly alter the stress-dilatancy relationship during virgin loading and its effects vanish with subsequent cyclic loadings as well.

Simulation of volumetric strain is also significantly improved after the damage and hardening factors are considered in the simulation of stress-strain relationship, and after considering the shrinkage and expansion of stress-dilatancy relationship with cyclic loading.

Comparison of undrained cyclic torsional shear test results with its simulation suggest that, after considering the effects of over-consolidation and slight shrinkage and expansion of stress-dilatancy relationship, the proposed model can reasonably simulate the generation of excess pore water pressure and stress-strain relationship of sand during undrained cyclic torsional shear loading, and capable of simulating the steady state during liquefaction and flow failure as well. However, the model needs further improvements to simulate the continuous increase of shear strain amplitude with cyclic loading after liquefaction as observed in dense sand. Liquefaction resistance of dense Toyoura sand specimens are slightly underestimated by the proposed model hence simulation becomes more conservative in case of dense specimens, while experimentally evaluated liquefaction resistance of loose specimens is similar to that obtained from the model.