Abstract

Deformation properties of sand with initial static shear in undrained cyclic torsional shear tests and their modeling

（初期せん断を受けた砂の非排水繰返しねじりせん断試験時の変形挙動とそのモデル化）

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Slope failure has been one of the most serious geotechnical disasters caused by earthquakes that produced substantial economic loss and killed a great number of people. Yet, its mechanism is not well understood; in particular the catastrophic liquefaction-induced failure behavior of natural and artificial slopes of sandy deposits and the consequent development of extremely large ground deformation is only poorly understood.

Soil elements within the sloped ground are subjected to an initial static shear stress on the horizontal plane or an assumed failure plane. During earthquake shaking, these elements are subjected to additional cyclic shear stress due to shear waves propagating vertically upward from the bedrock. The superimposition of static and cyclic shear stresses can have major effects on the response of soil, leading to liquefaction-induced failure of natural and artificial slopes of sandy deposits and the consequent development of extremely large ground deformation.

As far as the authors have investigated in the literature, there exists no previous study on the role of initial static shear stress on the undrained cyclic behavior of saturated sand in which the strain level could exceed more than 20 %. In previous studies, in the case of simple shear tests or torsional shear tests, the shear strain level was limited to 10 % due mainly to mechanical limitation of the employed apparatus; as well, in the case of triaxial tests, due to larger extents of non-uniform deformation of the specimen at higher strain levels, the axial strain level could not exceed 20 %.

With the intention of investigating the effects of initial shear stress on the large deformation properties of loose sand with initial static shear, a series of undrained cyclic torsional shear tests were performed on saturated loose Toyoura sand specimens up to single amplitude of shear strain of about 50 % under various combinations of static and subsequent cyclic shear stresses.

From the study of failure mechanisms, based on the difference in the effective stress path and the modes of development of shear strain during both monotonic and cyclic undrained torsional shear loading, the observed types of failure could be distinguished into three types: cyclic liquefaction (LQ), rapid flow liquefaction (RF) and residual deformation (RD) failures.

It was found that the failure behavior is a consequence of the degree of reversal loading. In fact, in case of stress reversal and intermediate loadings, failure could be associated with full liquefaction, followed by extremely large deformation in the post-liquefaction process (i.e., LQ and RF failure behaviors). On the other hand, in the case of non-reversal loading, the residual deformation brought the specimen to failure (i.e., formation of spiral shear band) although liquefaction did not occur.

The test results showed that the presence of initial static shear does not always lead to an increase in the resistance to liquefaction and strain accumulation; in fact, both can either increase or decrease by increasing the static shear depending on the extent of stress reversal and the failure behavior. However, in this study it was found that the two-phase change in liquefaction resistance (i.e., strictly speaking resistance against strain accumulation) can be associated with a two-phase change in the failure behavior from LQ to RF and from RF to RD.

The mode of development of residual deformation exceeding 50% was also investigated. It was found that large deformation could be developed in different ways according with the type of failure that sand experienced.

To simulate the behavior of saturated sand under undrained cyclic loading which leads to liquefaction and large cyclic shear strain development, an elasto-plastic constitutive model which can describe both monotonic and cyclic torsional shear behaviors of saturated sand under drained or undrained condition was developed at IIS (Institute of Industrial Science), University of Tokyo.

It is noteworthy that the motivation of the current study comes from the successful attempts as above described in simulating the liquefaction behavior of sand as well the cyclic large deformation behavior. However, no attempt has been made so far to model the undrained behavior of sand by considering the effect of static shear.

With the aim of simulating the behavior of saturated sand with initial static shear undergoing undrained cyclic loading which leads to liquefaction and large cyclic shear strain development, an elasto-plastic constitutive model which can describe both monotonic and cyclic torsional shear behaviors of saturated sand with initial static shear under drained or undrained condition was presented in this study.

The proposed model could simulate the behavior of loose saturated sand subjected to undrained torsional shear loading, under general conditions of stress reversal, intermediate and non-reversal loadings by varying the initial static shear and the amplitude of the subsequent cyclic shear stresses (i.e., varying the degree of reversal stress).

The liquefaction behavior of sand, described in terms of effective stress path, could be qualitatively modeled until the specimen enters into a full liquefaction state ($p'=0$), as well as during the cyclic mobility process. The stress-strain relationship could be qualitatively simulated up to a strain level of 8% until the specimens enter into a steady state.

The simulation results of both monotonic and cyclic undrained behavior could be employed to evaluate the failure behavior of sand. Therefore, cyclic liquefaction (LQ), rapid flow liquefaction (RF) and residual deformation (RD) failures were simulated. As well, by conducting additional numerical simulations, the behavior called as no-liquefaction and no-failure (NN), in which either liquefaction or failure did not take place even after applying several tens of cycles, could be defined.

Simulation results confirmed that the resistance against strain accumulation can either increase or decrease depending on the extent of reversal stress and the type of failure; in addition, it was confirmed by numerical simulations that the mode of development of residual deformation depends on the type of failure of sand.

Soils that are susceptible to liquefaction consist substantially of saturated uniform grain size distributions deposited in loose states. However, the fact that a soil is susceptible to liquefaction does not guarantee that liquefaction will be actually initiated during an earthquake event. It is also recognized that the stress conditions (confining pressure, cyclic shear and initial static shear stresses) play an important role in the liquefaction behavior of soil, the type of failure mechanism and the mode of development of soil deformation, especially in the case of slopes of sandy deposits. Many studies on the liquefaction of sand, including the current one, show that under non-reversal stress conditions saturated loose sand most likely will not experience liquefaction. However, this does not mean that sand is very resistant against seismic loading; in fact, a significant magnitude of combined static and cyclic shear stresses may cause failure of soil even though liquefaction does not take place. For these reasons, it is definitely important not only to have a clear understanding of the liquefaction mechanisms, but also to carry out in depth investigation on the effects of static shear on the failure modes of saturated sandy soil during undrained shearing.

With the scope of gaining a better understanding of the failure mechanisms of saturated sand, a method used to assess the failure behavior of sand specimens with initial static shear under undrained cyclic torsional shear loading was presented.

The proposed method is defined by means of three parameters namely: (i) static stress ratio $SSR = \tau_{static} / p_0'$, (ii) cyclic stress ratio $CSR = \tau_{cyclic} / p_0'$, and (iii) undrained monotonic peak stress ratio $MPSR = \tau_{peak} / p_0'$; where: τ_{static} = the initial static shear stress; τ_{cyclic} = the single amplitude cyclic shear stress; τ_{peak} = the shear stress at peak state during the undrained monotonic loading ; and p_0' = the initial effective confining pressure. The *SSR* corresponds to the driving shear force induced by the inclination of slopes; the *CSR* represents the inertial force exerted by earthquakes; while the *MPSR* takes into account the strength of soil which depends on the soil properties (e.g., relative density, etc) and the stress conditions.

By this method, called the "*Four-zone CSR/MPSR vs. SSR/MPSR method*", the initial static shear stress and the cyclic shear stress, measured in terms of SSR/MPSR and CSR/MPSR, respectively, were compared with the stress reversal line (i.e., SSR/MPSR = CSR/MPSR) and the undrained peak strength line (i.e., SSR/MPSR + CSR/MPSR =1). In accordance with the failure zone that these stress conditions correspond, the type of failure behavior of sand (i.e., LQ, RF, RD or NN) could be established.

Its applicability was investigated on a wide range of combinations of static and cyclic shear stresses on very loose, loose and dense sand by referring to: (i) the results of undrained cyclic torsional shear tests; and (ii) a number of single-element numerical simulations by employing the elasto-plastic constitutive model presented in this study.

On the basis of field data investigations from case histories of liquefaction-induced failure of sandy slopes during past earthquakes, the proposed method was used to compare the sand failure characteristics observed in the laboratory with the failure of slopes on site.