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Effects of initial static shear on liquefaction and large deformation properties of loose saturated Toyoura sand in undrained cyclic torsional shear tests

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Abstract

This study focused on the role which static shear plays on the large deformation behavior of loose saturated sand during undrained cyclic loading. A series of undrained cyclic torsional shear tests was performed on saturated Toyoura sand specimens up to single amplitude shear strain exceeding 50%. Three types of cyclic loading patterns, i.e., stress reversal, intermediate and non-reversal, were employed by varying the initial static shear level and the cyclic shear stress amplitude. The observed types of failure could be distinguished into liquefaction (cyclic and rapid flow) and residual deformation by comparing both monotonic and cyclic undrained behavior. It was found that the presence of initial static shear does not always lead to an increase in the resistance to liquefaction or strain accumulation; they could either increase or decrease with an increasing initial static shear level depending on the type of loading pattern and failure behavior. In addition, according to the failure behavior which the specimens exhibited, three modes of development of large residual deformation were observed.

Keywords: Large strain; Liquefaction; Static shear stress; Torsional shear tests; Undrained cyclic behavior

Introduction

Slope failure is one of the most serious geotechnical disasters brought about by earthquakes that may cause substantial economical losses as well as a great number of human losses. 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 are both poorly understood.

Past large-magnitude earthquakes (e.g., the 1964 Niigata Earthquake and the 1983 Nihonkai-Chubu Earthquake in Japan) have indicated that extremely large horizontal ground deformation can occur in liquefied sandy deposits in coastal or river areas. When lateral spreading and/or flow slides take place, ground displacement may exceed several meters, even in gentle slopes with an inclination of less than a few percent, resulting in severe damage to

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buildings, infrastructures and lifeline facilities (Hamada et al., 1994).

It is recognized that the behavior of soil elements within a sloped ground composed of saturated sands is different from that of a level ground during cyclic loading. This is because the soil elements are subjected to an initial static shear stress on the horizontal plane or an assumed failure surface. 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 stress can have a major effect on the response of the soil, leading to liquefaction and the development of extremely large ground deformation.

Various studies have focused on the effects of static shear on the undrained cyclic triaxial behavior of sand. Lee and Seed (1967) and Seed (1968) found that the larger the ratio of initial static shear stress to initial confining pressure acting on a horizontal plane, the greater the horizontal cyclic shear stress required to induce liquefaction in a given number of stress cycles. Furthermore, Vaid and Chern (1983) showed that the cyclic strength can either increase or decrease due to the presence of static shear stress and depending on the difference in density of the specimens, the magnitude of the static shear and the definition of liquefaction resistance. In particular, for loose sand with higher initial static shear, the cyclic strength was reduced due to flow deformation. Based on the difference in the effective stress paths and the stress–strain relationships, Hyodo et al. (1991) classified the undrained cyclic behavior of anisotropically consolidated specimens into three types, i.e., stress reversal, non-reversal and intermediate. They observed that in the stress reversal and intermediate cases on loose samples, failure could be associated with liquefaction, while in the non-reversal case, residual deformation brought the sample to failure even though no liquefaction had occurred. Failure was not observed in the non-reversal case on dense specimens. Recent work by Yang and Sze (2011) involved an investigation of the interdependence of major factors affecting the liquefaction behavior of sand, such as relative density, confining pressure and static shear. Clearly, the initial static shear stress has a significant effect on the liquefaction resistance, which is dependent on the initial relative density and the confining pressure. In addition, there are three different failure modes for sand under undrained triaxial cyclic loadings, namely, flow-type failure, cyclic mobility and accumulated plastic strain. Among these, the flow-type failure is the most critical, since it is characterized by abrupt, runaway deformations with no warning signals.

It is recognized that simple shear tests simulate field stress conditions expected during earthquakes more accurately than triaxial tests. The conclusions achieved by Yoshimi and Oh-oka (1975), through the performance of ring shear tests, were substantially opposite to those based on the triaxial tests by Lee and Seed (1967) and Seed (1968). They pointed out that to induce liquefaction and the development of large cyclic shear strain, the reversal of shear stress is necessary. Vaid and Finn (1979) evaluated the cyclic loading behavior of Ottawa sand under plane strain conditions using a simple shear device. They clarified that, in general, the resistance to liquefaction can either increase or decrease due to the presence of static shear and depending on the relative density of the specimens, the magnitude of the initial static shear stress and the shear strain level of interest. Tatsuoka et al. (1982) investigated the stress–strain behavior of sand under torsional simple shear conditions, including the case with static shear. Their results were well in accordance with those reported by Vaid and Finn (1979), confirming that a torsional simple shear apparatus could be employed as a very useful tool for evaluating the cyclic undrained stress–strain behavior of sand.

However, it should be noted that in all of the above studies, the shear strain levels employed were limited to the range of 10–20%. This is due mainly to the mechanical limitations of the employed apparatus and/or the large extent of the non-uniform deformation of the specimen at higher strain levels, as well as the technical difficulties involved with correcting the effects of the membrane force during the tests.

Therefore, it is not possible to fully describe the occurrence of a liquefaction-induced ground deformation of several meters, which means that ground strain may reach over 100% on a slightly sloped ground.

Based on the above-mentioned background, the aim of this study is to better understand the role which static shear plays on the large deformation behavior of loose saturated sand during undrained cyclic loading. In this paper, the results of investigations on the effects of the initial static shear on the undrained cyclic behavior of saturated Toyoura sand specimens, subjected to cyclic torsional shear loading up to single amplitude of about 50% under various combinations of static and subsequent cyclic shear, are presented.

Test apparatus

To reach extremely large torsional shear displacements, a fully automated torque-loading apparatus on hollow cylindrical specimens (Fig. 1), developed by Koseki et al. (2007) and Kiyota et al. (2008), was employed. It is capable of achieving double-amplitude torsional shear strain levels exceeding 100% by using a belt-driven torsional loading system that is connected to an AC servo motor through electro-magnetic clutches and a series of reduction gears.

A two-component load cell, which is installed inside the pressure cell, as shown in Fig. 1(a), having torque and axial load capacities of 0.15 kNm and 8 kN, respectively, was used to measure both the torque and the axial load components. The confining pressure, obtained by the difference in pressure levels between the cell pressure and the pore water pressure, was measured by a high-capacity differential pressure transducer (HCDPT) with a capacity of over 600 kPa. To evaluate