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Estimation of liquefaction potential from dry and saturated sandy soils under drained constant volume cyclic simple shear loading

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ABSTRACT

Understanding the liquefaction mechanism of sandy soils still remains as one of the challenges in geotechnical earthquake engineering, since clean sands, silty sands and clayey sands do not necessarily show identical reactions under seismic loading. This study investigates the cyclic simple shear responses of three sandy soils: clean sand (Sile Sand 20/55), silty sand (Sile Sand 20/55 with 10% IZ silt) and clayey sand (Sile Sand 20/55 with 10% kaolin) based on many dry and saturated specimens. Drained constant volume cyclic simple shear tests on clean and silty sand specimens have shown that liquefaction potential of those soils could also be determined via dry samples. This is an important observation, since dry specimens are much easier to prepare and less time consuming compared to their saturated counterparts, as the demanding saturation process is eliminated. However, cyclic responses of dry and saturated clayey sand specimens were shown to be quite different, and therefore saturation of these specimens is still a must for liquefaction assessment. For both silt and kaolin, adding 10% fines to the base sand increased the liquefaction potential of resulting sandy soils considerably compared to the clean sand at the same void ratio. But this difference relatively decreased as the specimens became looser.

1. Introduction

Liquefaction of sandy soils is among the most investigated topics of modern geotechnical engineering but still remains to be one of the most challenging aspects of earthquake geotechnics. Field observations have shown that the predominant soil type in many of the liquefied sites were sandy soils involving certain amount of fines. Lade and Yamamuro [27] gave a summary of 20 cases of static or flow-type liquefaction and about 40 cases of seismic liquefaction. Those liquefaction cases occurred at various geotechnical structures including submarine slopes, mine tailings, hydraulic fills, spoil heaps, highway embankments, levees, level grounds and earth dams. Fourtynine out of fiftynine liquefaction case histories reported by Lade et al. [33] involved sands with certain amount of fines. Cetin et al. [13] analyzed 201 field case histories and proposed an SPT based probabilistic correlation for liquefaction assessment. One hundred and fiftyeight out of 201 case histories analyzed by Cetin et al. [13] involved sands with certain amount of fines (i.e. FC > 0).

Bardet and Kapuskar [5] mentioned liquefaction of sandy soils at the Marina District of San Francisco during the 1989 Loma Prieta Earthquake. Stewart et al. [48] wrote about several liquefaction sites involving fines containing sands during the 1999 Chi-Chi Earthquake in Taiwan. Bray et al. [10] reported that severely damaged city of Adapazarı, Turkey during 1999 Kocaeli Earthquake has a soil profile generally involving loose silts and silty sands at shallow depths up to 5 m and some of the liquefied layers contain considerable amounts of clay sized particles as well. Bhattacharya et al. [8] expressed widespread liquefaction hazards due to sandy soils, which ranged from sandy silt to silty sand, at the Tokyo Bay area during the 2011 Tohoku Eartquake (the largest earthquake ever recorded in Japan, with $M_w = 9$). Belkhatir et al. [7] denoted that significant loss of life and property occurred during 1980 Chlef Earthquake in Algeria, where various liquefaction cases involving sandy soils were observed. Taylor et al. [49] discussed the extensive damage at the Central Business District of Christchurch caused by liquefaction during the 2011 Christchurch Earthquake series. Accordingly, the upper 8 m of profile consists of soils ranging from silty fine sands to sandy silts with fines contents between 15% and 50%.

Observations of liquefaction cases from various earthquakes mentioned above revealed two major aspects regarding the liquefaction research: 1) investigating the liquefaction of clean sands is important

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but not sufficient, as many of the in-situ liquefaction cases involve sandy soils involving certain silt or clay fractions. Hence, research should focus more on silty and/or clayey sands' behavior. 2) In parallel to the first aspect, laboratory investigation and liquefaction experiments in a controlled environment has still vital importance to understand the influence of various factors such as fines type, fines content, plasticity, grain size, shape and distribution etc. on liquefaction potential of sandy soils containing silt and/or clay as fine particles. To investigate the influence of such factors, it is often required to reconstitute sandy soil specimens with controlled parameters such as fines content, gradation characteristics, fines' plasticity etc. This brings together the various challenges of specimen preparation process such as convenience of the applied deposition technique for the soil of interest (e.g. segregation and distribution of fines within the specimen could be a problem in wet pluviation based techniques) and obtaining high and repeatable degrees of saturation with varying fines content and type. There have been substantial studies regarding the comparison of different depositional methods and corresponding undrained response of sands [42,54] and silty sands [21,60,11].

Meanwhile, obtaining high and comparable degrees of saturation for different laboratory deposited sandy soil specimens containing fines still remains to be one of the difficult and demanding tasks of reliable specimen preparation for liquefaction research. Obtaining fully saturated laboratory deposited specimens for liquefaction research also requires a very time consuming procedure. As an example, Monkul and Yamamuro [32] used the dry funnel deposition technique for deposition of triaxial silty sand specimens. After the deposition, specimens were flushed with CO_2 in the dry state for 40 min and then de-aired water was percolated about 18.5 h to facilitate full saturation of specimens even before back pressure was applied. Hence, the saturation process of a single silty sand specimen took about 19 h for their study. Similarly, Hazirbaba [19] mentioned that silty sand specimens having more than 10% fines content (FC) required up to 48 h of back pressure application to achieve acceptable B values for cyclic simple shear testing.

In 1977, Finn and Vaid [18] mentioned an important observation about the liquefaction behavior of Ottawa sand in constant volume cyclic simple shear condition. Accordingly, dry and saturated sand specimens showed identical drained constant volume simple shear behavior. This is an important statement; because the liquefaction potential of a sand could be predicted from dry specimens, eliminating the demanding and time consuming saturation process. In the study of Finn and Vaid [18], no experimental data or graph specifically comparing saturated specimens with their dry counterparts in constant volume simple shear were provided. Instead, it was clearly emphasized that no practical differences were found between the two. Up to the present, no experimental verification was available in the literature. Furthermore, it is unknown whether such a statement is valid for sands involving certain silt or clay fractions.

The goal of this study is to investigate whether liquefaction potential of clean sands, silty sands and clayey sands could be predicted from dry soil specimens. Drained constant volume cyclic simple shear tests were performed on various fully saturated and dry sandy soil specimens. The resulting behaviors are compared and the possibility of predicting liquefaction potential from dry specimens is discussed depending on the soil type (i.e. clean sand, silty sand or clayey sand).

2. Cyclic simple shear testing and experimental setup

Cyclic simple shear is probably the most popular laboratory test to investigate the dynamic behavior of soils after the cyclic triaxial testing. Cyclic simple shear testing has some advantages over cyclic triaxial testing. Cyclic loading mechanism in simple shear test resembles the earthquake loading conditions better compared to the cyclic triaxial test. Consolidation in simple shear is anisotropic, and can be assumed to represent at rest condition in the field. Also specimen preparation is relatively easier compared to that for triaxial testing, mainly due to the smaller size of simple shear specimens with respect to the typical triaxial test specimens.

Early developments of simple shear testing were initiated in UK [43] and Scandinavia at SGI [24] and at NGI [9]. Later, Peacock and Seed [38] adapted it to cyclic loading for liquefaction research. Two alternatives exist in modern simple shear testing to represent the volumetric conditions under dynamic loading in the field: “undrained” and “drained constant volume” testing. In undrained simple shear testing, the specimens could be enclosed in a pressure chamber similar to the triaxial testing. Some researchers kept the vertical stress constant [16], while some others kept the consolidated height of the specimen constant during shearing [20,14,22]. Regardless, the specimens are sheared in undrained conditions and the generated excess pore pressures are measured with a pore pressure transducer.

In drained constant volume simple shearing, specimens are sheared in drained conditions in such a way that the volume of the specimens is kept constant during the entire shearing stage. Since, volumetric strain is equal to the axial strain in a simple shear test, constant volume is preserved by adjusting the magnitude of the vertical stress on the specimen so that the height of specimen does not change during shearing. Because drainage is allowed, no pore pressure is measured with a transducer, and the change of vertical stress is used to predict the excess pore pressures in an equivalent undrained test [9]. Dyvik et al. [16] demonstrated on normally consolidated clay that pore pressures measured in an undrained simple shear test is identical with the pore pressures predicted from a drained constant volume simple shear test. Following this verification, drained constant volume type of simple shear testing was also frequently used in liquefaction research [53,41,55,46,23].

In this study, an NGI type Geocomp cyclic simple shear device at Yeditepe University was used and the tests were done in drained constant volume condition. The typical specimens have a diameter of 64 mm and a height of 20 mm. The lateral confinement was provided by aligning several teflon coated rings around a conventional latex membrane. Typically, steel-wire-reinforced membranes are used in most NGI type devices in order to provide lateral confinement, even though ASTM [2], suggests to use either rings or a wire-reinforced membrane. Recently, Baxter et al. [6] compared the response of specimens confined with wire reinforced membrane and teflon coated rings with a Geocomp simple shear apparatus. Accordingly, teflon rings give more lateral stiffness during the consolidation stage, but the stress–strain response during shearing was similar for the two confinement systems.

As mentioned before, pore pressure measurements and therefore the degree of saturation is not a concern for drained constant volume type of simple shearing (i.e. decrease in vertical stress to maintain constant height is equivalent to an increase in excess pore water pressure). Consequently, many of the typical simple shear devices of this type are not inherently designed for the challenging procedure of specimen saturation. Since the main goal of this study is comparing the responses of various fully saturated and dry sandy soil specimens, the bottom platen of the device in this study is modified in order to allow CO_2 flushing and de-aired water percolation for obtaining fully saturated specimens. Note that the specimens in this study were either dry or fully saturated therefore; issues with partial saturation were not a concern during the discussion of the findings.

3. Soils tested and specimen preparation

The base sand used in this study was obtained from a sand quarry at the Sile region of Istanbul and named as Sile Sand 20/55. This sand