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Undrained shear strength of desaturated loose sand under monotonic shearing

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Abstract

Previous studies have shown that desaturation can improve the liquefaction resistance of originally saturated sand. To apply this method in practice, we need to establish the relationship between undrained liquefaction resistance and the degree of saturation for sand. In this paper, previous studies on the undrained strength and liquefaction behavior of partly saturated sand are reviewed first. Then, experimental results of triaxial undrained compression and extension tests on loose sands are presented. The data are used to examine the relationships between undrained liquefaction resistance and degree of saturation of samples under different loading modes.

Keywords: Liquefaction; Soil desaturation; Undrained shear strength

1. Introduction

Previous studies on the liquefaction behavior of sand have shown that one way to increase the liquefaction resistance of sand is to make it slightly unsaturated (Yang et al., 2004; Okamura and Soga, 2006; Yegian et al., 2007; Okamura et al., 2011; He et al., 2013). During undrained shearing, isolated gas bubbles in sand can largely alleviate the pore water pressure buildup which would have been generated in fully saturated sand and enhance the undrained shear strength of desaturated sand. This desaturation approach is potentially less expensive than other conventional liquefaction remedial methods. It also offers an alternative mitigation solution to liquefiable sites where soil compaction or cement mixing is deemed too difficult to be carried out. In order for this method to be applied reliably in practice, a proper design procedure has to be established. The objectives of this study are to achieve a better understanding on how desaturation affects the undrained resistance of sand through a set of laboratory tests. The testing data were used to verify some of the established relationships between undrained strength and degree of saturation. The implication of the test results on post-liquefaction flow failure is also discussed.

2. Background

The undrained behavior of unsaturated sand has been a research topic of great interest for decades. Early studies on

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this topic were intended to prove the necessity of achieving full saturation in order to avoid overestimating undrained shear strength in triaxial tests (Sherif et al., 1977; Chaney, 1978; Yoshimi et al., 1989; Xia and Hu, 1991). In recent years, the objective of the research has been shifted to the use of soil desaturation as a means of liquefaction mitigation (Tsukamoto et al., 2002; Tamura et al., 2002; Pietruszczak et al., 2003; Yang et al., 2004; Okamura and Soga, 2006; Okamura et al., 2006, 2011; Yegian et al., 2007; Rebata-Landa and Santamarina, 2012; Eseller-Bayat et al., 2013; He et al., 2013). Some of these studies are reviewed below.

The relationship between cyclic strength and degree of saturation has been investigated using cyclic triaxial or cyclic torsional shear tests, as summarized by Yang et al. (2004) and Okamura and Soga (2006). An increase in the cyclic strength of sand is observed when the degree of saturation or pore pressure coefficient B is reduced. Based on laboratory cyclic triaxial tests on sand, Okamura and Soga (2006) obtained a relationship to account for the increase in cyclic strength of sand with the change in degree of saturation, as:

$$LRR = \log(6500\varepsilon_v * + 10) \quad (1)$$

in which, LRR is the liquefaction resistance ratio which is defined as the strength of unsaturated sand normalized with respect to that of fully saturated sand, and ε_v^* is the potential volumetric strain which is calculated as

$$\varepsilon_v * = \frac{\sigma_c'}{p_0 + \sigma_c'}(1 - S_r)\frac{e}{1+e} \quad (2)$$

in which, p_0 is the absolute pressure of the pore fluid, $\sigma_c{}'$ is the initial effective confining pressure, S_r is the degree of saturation, and e is the initial void ratio.

Another relationship between the cyclic strength ratio and the pore pressure coefficient B was obtained by Yang et al. (2004) based on laboratory test data:

$$(\mathrm{CSR})_{\mathrm{PS}} = (\mathrm{CSR})_{\mathrm{FS}}\exp[\beta(1 - B)] \quad (3)$$

in which, CSR is the cyclic strength ratio, the subscripts PS and FS denotes partial saturation and full saturation, respectively, β is a parameter to be calibrated from the test results, and B is the pore pressure coefficient B. The value β of 0.71 was suggested to fit the cyclic test results. We can show by using these relationships that lowering the degree of saturation of an initially fully saturated sand by a few percent will lead to a significant enhancement in the cyclic strength. The logarithmic relationship as expressed in Eq. (1) suggests that the effect of desaturation on the liquefaction resistance is more pronounced when the degree of saturation is relatively high and the effect becomes weaker as the degree of saturation reduces. Moreover, other parameters, such as back pressure, effective confining pressure, and void ratio, also affect the strength of sand, as indicated by Eqs. (2) and (3) (note B is also a function of these parameters).

Shaking table model tests have also been carried out on sand slightly desaturated to different degrees of saturation to study the effect of desaturation on liquefaction resistance (Okamura and Teraoka, 2006; Yegian et al., 2007; He et al., 2013). The test results obtained from these tests indicate further that desaturation is effective in reducing the liquefaction responses, such as pore water pressure buildup, ground settlement, and sinking of structures resting on the soil.

The observation that the undrained strength of slightly unsaturated sand is higher than that of saturated sand is also manifested under monotonic loading. Grozic et al. (1999) reported that, under undrained compression, loose sand experienced a transition from strain softening to strain hardening when the degree of saturation was reduced to be lower than 90%. Rad et al. (1994) reported that sand containing nonsoluble gas is stronger than that containing soluble gas. The numerical modeling conducted by Grozic et al. (2005) showed that the undrained strength of gassy soil increased with a reduction in the degree of saturation. It should be pointed out that the objective of these studies was to investigate the effect of gas on the undrained behavior of gassy soil (soil with pore water containing dissolved gas) in marine sediments. This paper, however, aims at examining the relationship between the liquefaction resistance and the degree of saturation so as to evaluate the effectiveness of desaturation as a means for the liquefaction mitigation.

Different techniques to achieve the desaturation of sand have been proposed and tested, including air injection (Okamura et al., 2011), water electrolysis (Yegian et al., 2007), the use of chemicals, such as sodium perborate (Eseller-Bayat et al., 2013), and the use of microbial processes, such as microbial denitrification (Rebata-Landa and Santamarina, 2012; He et al., 2013). It is also reported that a soil improvement technique, sand compaction pile, can bring large amount of air bubbles into sand piles and surrounding soils, which has a positive effect in addition to its primary function (Okamura et al., 2006). The use of vacuum evaporation or vacuum pressure can also achieve the desaturation effect of soil, although this method is more applicable for fine grain soils (Umezaki and Kawamura, 2013). In this experimental study, the microbial denitrification process is adopted for soil desaturation, as will be introduced in detail in the next section.

Although liquefaction resistance should be evaluated using cyclic tests, liquefaction under quasi-static loading conditions is also important because quasi-static loading can be either the triggering factor of liquefaction or the driving force of postliquefaction flow failure under some conditions (Jefferies and Been, 2006). However, there are differences between cyclic and static liquefaction. Cyclic liquefaction can potentially occur in dense sand given abundant number of cycles (Yang et al., 2004; Okamura and Soga, 2006). In contrast, strain hardening (non-liquefaction) prevails in dense sand under monotonic loading irrespective of degree of saturation (He, 2013). Therefore, loose sand should be studied when static liquefaction is a concern.

In this paper, experimental results of triaxial undrained compression and extension tests on desaturated loose samples are presented. The relationships between liquefaction strength and degree of saturation under different loading conditions are summarized and discussed.