Influence of Imperfect Saturation on Deformation Characteristics and Pore Water Pressure Buildup Under Cyclic Loading for Sand

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This paper presents an influence of imperfect saturation on undrained deformation behavior for sand. A torsional shear apparatus is newly modified and capable of undrained shear tests and measurements of S- and P-wave velocities for a saturated soil specimen. S- and P-wave velocities were measured for various partially saturated sand specimens, and P-wave velocity was found to be very sensitive to imperfect saturation. Undrained torsional shear tests were performed at various partially saturated conditions, measuring excess pore water pressure; this decreases significantly as the degree of saturation decreases. Nonlinear deformation characteristics were slightly influenced by B-value at the mean effective stress of 30 kPa.

INTRODUCTION

Soils below the groundwater table including soft offshore sediments are generally considered to be fully saturated, yet they may not be. Near the groundwater table, there is a frequent inflow-drain process of water due to water level fluctuations, flooding, wave or man-made activity. The water-flow process possibly provides opportunity for air bubbles to migrate into pore water, resulting in a partially saturated condition below the groundwater table. Recent studies by Kokusho (2000), Tsukamoto et al. (2002) and Yoshimi et al. (1989) have found that the P-wave velocity ($V_p$) of soil deposits at a depth of several m even below the groundwater table mostly ranges between 600 m/s and 1300 m/s, but generally the $V_p$ of saturated soil is higher than 1500 m/s because the $V_p$ of pure water is 1500 m/s. The lower $V_p$ implies that the soil deposits may not be fully saturated because a large number of air bubbles could be trapped in pore spaces and cause the lower $V_p$. This could have a remarkable influence on the build up of pore water pressure in soils under undrained loading (earthquakes). It is then necessary to investigate the behaviors of this nearly saturated zone—which is typically assumed to be fully saturated in design practices—for the reliable evaluation of the behavior of soil deposits.

Yoshimi et al. (1989) made one of the first observations on the effect of saturation. They reported that the resistance to the onset of liquefaction in sandy soils tends to increase with a reduction in the degree of saturation ($S_r$), and they found that the liquefaction resistance at 70% saturation shows a nearly threefold increase over that at a fully saturated condition. Kim and Park (2008) assessed the liquefaction potential under an almost saturated condition using real earthquake loading. However, as $S_r$ is calculated by measuring the volume of a soil element, it is generally difficult to determine precisely when the soil element is nearly saturated. Thus in laboratory tests the pore water pressure coefficient ($B$) is commonly employed to quantify the state of saturation of a soil specimen, as the $B$-value is easily measured and sufficiently accurate to indicate partial saturation. The $B$-value as originally introduced by Skempton (1954) is given as:

$$B = \frac{\Delta u}{\Delta \sigma}$$

(1)

where $\Delta \sigma$ (kPa) is the increment of the confining pressure. $\Delta u$ (kPa) is the increment of the excess pore water pressure induced by $\Delta \sigma$ in an undrained condition.

Lade and Hernandez (1977) proposed a theoretical relationship between the $B$-value and $S_r$. Until $S_r$ is less than 90%, the $B$-value practically becomes zero, yet the $B$-value increases sharply with a small increment of $S_r$ after $S_r$ exceeds approximately 98%. Selim and Burak (2006) and Tsukamoto et al. (2002) evaluated the liquefaction resistance with various $B$-values from approximately zero (for 90% saturation) to over 0.95 (for full saturation). When the $B$-value approaches zero, the liquefaction resistance increases by approximately twice as much as that under a fully saturated condition. In addition, Yang and Sato (2001) simulated the influence of saturation on vertical motion amplification in a numerical simulation, concluding that partial saturation in soils may lead to greater amplification of the ground vertical motion than full saturation.

On the basis of these researches, the effects of $S_r$ or the $B$-value on the undrained behaviors of soils, in field as in laboratory, should be considered. Unfortunately, there is no effective method to directly monitor $S_r$ or the $B$-value in the field. $V_p$ has been recognized as one of the most sensitive parameters to the change of the $B$-value and the saturation of soils. Currently, the P-wave velocity ($V_p$) measurement has been popular at fieldsite investigations using field seismic tests: down-hole, refraction, reflection methods; the $V_p$ value can then be utilized in the field as a convenient index indicative of the state of saturation. However, utilizing $V_p$ for evaluation of saturation requires more extensive investigation in the relationship between $B$ and $V_p$ at various conditions as well as their effect on the undrained behavior of soil. This effort will help in characterizing partially saturated zones as well as evaluating undrained behaviors for in-situ soil deposit.

In this paper, an extensive experimental study was carried out by using a newly improved torsional shear (TS) testing system to investigate dynamic soil properties and pore water pressure buildup for nearly saturated sands. First, a Stokoe-type TS testing system was improved in an effort to saturate a soil specimen and measure the excess pore water pressure buildup induced by undrained cyclic loading. In addition, the new TS testing system...