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Impact of hydraulic hysteresis on the small strain shear modulus of unsaturated sand

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Abstract

The results of previous studies on silt and clay indicated that variations in the small strain shear modulus, G_{max}, during hydraulic hysteresis had a non-linear increasing trend with matric suction, with greater values upon wetting. However, due to differences in material properties and inter-particle forces, a different behavior is expected for the G_{max} of unsaturated sand. Although considerable research has been devoted in recent years to characterizing the behavior of the G_{max} of sand during drying, less attention has been paid to the effect of hydraulic hysteresis on G_{max} and its variations during wetting. In the study presented herein, an effective stress-based semi-empirical model was developed to predict the variations in the G_{max} of unsaturated sand during hydraulic hysteresis. The proposed model incorporated the impact of the possible changes in volume through an empirical void ratio function as well as the effect of the degree of saturation through the use of suction stress. The effective stress was also defined using the concept of suction stress. The efficiency of the proposed model was evaluated by comparing the model predictions with the results of an experimental testing program involving the measurement of the G_{max} of sand with different grain size distributions during hydraulic hysteresis. Specifically, a suction-controlled triaxial testing device, equipped with a pair of bender elements, was used to define the hysteretic trends in G_{max} for different values of mean net stress. The model was found to provide satisfactory predictions of the trends in G_{max} with matric suction, as well as its peak value and the suction corresponding to the occurrence of the peak G_{max}. It also provided satisfactory predictions of the variations in G_{max} upon subsequent wetting.

Keywords: Small strain shear modulus; Unsaturated sand; Bender element; Hydraulic hysteresis; Semi-empirical model; Suction stress

1. Introduction

In recent years, extensive research has been done on the role of the degree of saturation S_r and matric suction ψ on the shear wave velocity and $G_{\max}$ of unsaturated sand (Wu et al., 1984; Qian et al., 1991; Picornell and Nazarian, 1998; Cho and Santamarina, 2001; Kim et al., 2003; Takkabutr, 2006; Lee et al., 2007; Khosravi et al., 2010; Ghayoomi, 2011; Nyunt et al., 2011; Asslan and Wuttke, 2012; Kumar and Madhusudhan, 2012; Oh and Vanapalli, 2014; Dong et al., 2016). The results of these studies indicated that S_r and ψ exert a great influence on the behavior of $G_{\max}$. However, in contrast to silt and clay, in which a clear and specified trend for $G_{\max}$ with respect to S_r was reported (Ng et al., 2009; Khosravi, 2011; Khosravi and McCartney, 2011, 2012; Khosravi et al., 2016a), the $G_{\max}$ of sand was observed to behave differently with a decrease in S_r. The $G_{\max}$ of sand with a uniform grain size distribution varied mostly in an up-and-down manner with changes in S_r during drying and with a maximum value that could occur at any degree of saturation (Wu et al., 1984; Qian et al., 1991; Khosravi et al., 2010; Ghayoomi,

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2011; Kumar and Madhusudhan, 2012; Khosravi et al., 2016b). The results of studies on well-graded sand, on the other hand, showed that the tested soil may vary in moisture content over a wider range of suction, resulting in a $G_{\max}$ behavior similar to the well-known continuously-increasing trend for the $G_{\max}$ of silt and clay (Kim et al., 2003; Lee et al., 2007).

The results of former studies have allowed for the development of some predictive models which related the $G_{\max}$ of unsaturated sand to the void ratio, confining stress, and Soil Water Retention Curve, SWRC, components (Khosravi et al., 2010; Oh and Vanapalli, 2014; Dong et al., 2016). However, the proposed models only investigated the variations in the $G_{\max}$ of sand during drying. The impact of hydraulic hysteresis was not taken into consideration. As such, there is no suitable model for accurately predicting the G_{max} of sand along different paths of drying and wetting.

The aim of this paper is to identify the trends of $G_{\max}$ for unsaturated sand during hydraulic hysteresis. Specifically, a series of bender element tests are carried out in a modified triaxial testing device with suction-saturation control to interpret the role of suction stress, p_s, and S_r on the $G_{\max}$ behavior in unsaturated sand. The modified setup allows for the precise control of mean net stress p_n and matric suction ψ to magnitudes as low as 0.1 kPa. The results of this study are also used to develop a semi-empirical model to capture the behavior of $G_{\max}$ during hydraulic hysteresis for unsaturated sand.

2. Background

Ghayoomi et al. (2012) performed a series of physical model centrifuge tests to simulate ground motions and studied the settlement behavior of an unsaturated layer of sand during seismic loading. The results of this study revealed the significant effect of S_r on soil settlement behavior during seismic loading. The soil settlement-S_r curve showed an initial decrease in settlement during drying to a specific point at the S_r value of approximately 0.45, followed by an increasing trend (Fig. 1). An interesting observation in their study was that the trend for soil settlement was found to be consistent with the shape of the $G_{\max}$-S_r curve during drying (Fig. 1). From the results of the centrifuge tests, Ghayoomi et al. (2012) proposed and verified an empirical methodology for predicting the seismic-induced settlement of a free field unsaturated sand layer. The new methodology incorporated recent advances in definitions of the effective stress and stiffness in unsaturated soil, as well as soil-water retention curve parameters, into the existing approaches originally developed for saturated soil. In particular, the small strain shear modulus was defined using an effective stress-based approach proposed by Khosravi et al. (2010).

Khosravi et al. (2010) investigated the effects of the effective stress components on the $G_{\max}$ of silica sand using a Stokoe-type resonant column testing device adapted with

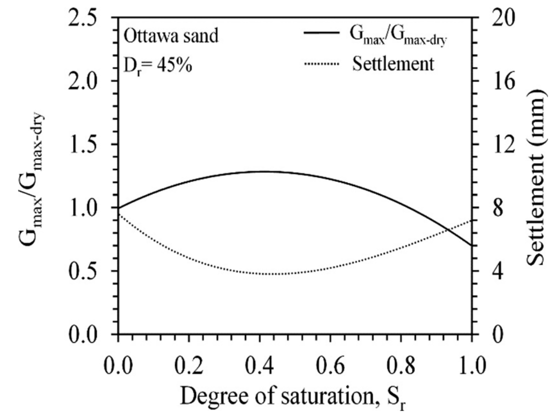

Fig. 1. $G_{max}/G_{max\text{-}dry}$ and settlement variation with S_r (Ghayoomi, 2011).

a hanging column setup for suction control. The results of their study indicated an initial increase in $G_{\max}$ during drying to a peak value at a matric suction corresponding to the residual condition, followed by a decreasing trend. Furthermore, an increase in p_n led to a significant increase in the stiffness of soil, and consequently, in its $G_{\max}$ value. Based on their findings, the following approach was proposed to characterize the possible changes in the $G_{\max}$ of unsaturated sand during drying:

$$G_{\max} = \frac{A}{0.3 + 0.7e^2} p'^n \tag{1}$$

where A and n are fitting parameters, e is the initial void ratio, and p' is the mean effective stress. The approach was defined using the concept of suction stress, proposed by Lu and Likos (2006), as follows:

$$p' = p_n + p_s \tag{2}$$

In this equation, p_n and p_s are the mean net stress and suction stress, respectively. Suction stress is a stress variable that incorporates the effect of different inter-particle stresses arising from chemical cementation, van der Waals attraction, capillarity, and double-layer repulsion into the effective stress definition for unsaturated soil (Lu and Likos, 2006). Mean net stress is simply defined as the difference between the total mean stress, p, and the pore air pressure, u_a ($p_n = p - u_a$).

Oh and Vanapalli (2014) used the concept of independent stress state variables, proposed by Fredlund and Morgenstern (1977), for the state of stress in unsaturated soil and proposed a semi-empirical model to represent the magnitude of $G_{\max}$ for unsaturated non-plastic sand using the following equation:

$$G_{\max} = G_{\max 0}\left[1 + \varsigma\left(\frac{101.3\psi}{P_a}\right)S_r^{\xi}\right] \tag{3}$$

where $G_{\max 0}$ is the small strain shear modulus at the saturated condition, P_a is the atmospheric pressure, and ς and ζ are the grain-size distribution parameters. The model was then validated against experimental results reported in literature. Recent studies by Dong et al. (2016) and Dong

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