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Effects of principal stress rotation on small strain stiffness of sand subjected to piping erosion

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Abstract

Along with the development of experimental techniques and numerical simulations, knowledge of the mechanism of the internal erosion process and the resulting failures has increased remarkably. Despite such advancements, little attention has been paid to the soil after erosion, whose dominant characteristic is the significant anisotropic fabric represented by discontinuities in the erosion planes. In this research, in order to investigate the small strain stiffness of eroded soil, a proposal for generating the local disturbance in the form of piping was achieved by dissolving pre-placed glucose in soil samples. A series of experiments on specimens with determined eroded planes was conducted in a hollow cylindrical torsional shear apparatus. For both the intact and the eroded specimens, the elastic shear modulus was evaluated at various stress states with the help of gap sensors under small-amplitude torsional cyclic loadings. The stress directional dependency of G was examined by changing the principal stress axes while keeping mean effective stress p' and stress ratio σ'_1/σ'_3 constant. According to the results, a marked reduction in the shear modulus was induced after piping erosion, and the stiffness of the eroded soil was found to be sensitive to changes in the stress directions due to the resultant anisotropic fabric involving the loss of inter-particle contacts and the rearrangement of sand particles.

Keywords: Piping erosion; Shear modulus; Dissolution; Torsional cyclic loading; Particle loss

1. Introduction

Landslides caused by piping during the rainy season have been reported in numerous countries and have recently begun to draw the attention of geotechnical engineers (Pierson, 1983; Jones, 1987; Uchida et al., 2001; Richards and Reddy, 2007). It is commonly observed that chains of connected macro-pores develop in parallel to the sand layer on a damaged slope. Such soil pipes not only have a significant impact on the hydraulic conductivity of the ground, but also contribute to the movement of sediment on slopes as well as to the re-initiation of landslides.

Piping occurs when water flows through a cavity, crack or other continuous void within the soil. As one of the most common forms of internal erosion, piping puts the stability of a slope at great risk due to the fact that its resultant external evidence is too subtle to be observed in time even when severe migration of the soil particles has already taken place.

Based on the statistics of past incidents and field observations, comprehensive research was done to clarify the mechanisms of internal erosion and to reduce the damage it can cause. Large-scale model tests, focusing on the progression of erosion, were carried out in order to understand the failure process of dikes and levees under concentrated

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Nomenclature

α inclination of major principal stress direction to vertical
C_G correction factors
D_o, D_i inner and outer diameters of specimen
D_{ini} relative density at confining stress of 80 kPa at dry state (sand only)
e void ratio
e_{ini} void ratio at confining stress of 80 kPa at dry state
e_p void ratio at confining stress of 80 kPa after dissolution of glucose
$f(e)$ void ratio function
G_{ini} shear modulus at confining stress of 80 kPa at dry state
G_p shear modulus at confining stress of 80 kPa after dissolution of glucose
$G_{z\theta}$ shear modulus in (z, θ) plane
G_{ijo} shear modulus G_{ij} at reference stress state
H height of specimen
k_n factor for the principal stress ratio
n power
p' mean effective stress
r_o, r_i inner and outer radii of specimen
r_p, r_s radii of specimen for piping-influenced part and sand only part
γ shear strain
ε_z, ε_r, ε_θ vertical strain, radial strain, circumferential strain
τ shear stress
σ_z, σ_r, σ_θ vertical stress, radial stress, circumferential stress
σ'_1, σ'_2, σ'_3 effective major, intermediate and minor principal stress

leakage. As a continuation of the pinhole test (Sherard et al., 1976), quantitative tests, such as the hole erosion test (Wan and Fell, 2004; Benahmed and Bonelli, 2012) and the jet erosion test (Hanson and Cook, 2004) were designed to assess the piping erosion characteristics of soils, in which the major concerns include the hydraulic gradient, the geometric conditions, the erodibility of soils, the loading conditions, etc. In addition, based on Richards' equation, a considerable number of numerical approaches for modelling the macropore flow and the pipe flow have been proposed (Kosugi et al., 2004; Akay et al., 2008; Sharma et al., 2009), in which the soil pipe was treated as a highly conductive porous medium or a porous medium-filled domain. However, obvious hurdles still exist due to the difficulties in interpreting and modelling the dynamic preferential flow, the internal mass failures and the particle transport processes that change with time.

Despite the wealth of research on the causes and consequences of piping, questions arise as to exactly how the changes in soil fabric due to particle removal affect the mechanical properties of soil. In the past few years, laboratory studies using sand-salt mixtures have allowed insights into the engineering behavior of soil structures containing water-soluble minerals (Shin and Santamarina, 2009; Truong et al., 2010). Through dissolution tests on controlled artificial specimens, the steps of internal erosion, such as suffusion, could also be reproduced in a more convenient way. In these experimental studies, the consequences of particle dissolution to the strength and deformation behavior of soils have been widely investigated, and it has been repeatedly reported that particle loss will lead to marked settlement strain, an increase in the void ratio and a weakening of the overall strength. Only limited research has been performed focusing on the stiffness characteristics of soils under the effect of internal erosion, although it is of great importance to the deformational analyses of earthquakes, machine foundations and other types of dynamic loading.

Fam et al. (2002) conducted dissolution tests using mixtures of sand and fine-grained salt to study the evolution of small-strain properties during dissolution. They observed as much as a 25% reduction in shear wave velocity for a 10%-salt mixture (by weight) during dissolution. A similar conclusion for the decrease in shear-wave velocity after dissolution was also reported by Truong et al. (2010), in which various percentages of salt by volume were tested in an oedometer equipped with bender elements. It was stated that the magnitudes of the variations in void ratio and shear wave velocity were found to be proportional to the initial salt fractions. This was also mentioned in the study by Kelly et al. (2012), where a majority of the samples with salt particles at a percentage mass of 15% experienced a decrease in shear-wave velocity of approximately 40%.

The above findings from dissolution tests are based on the assumption that the internal volumetric strain caused by particle dissolution follows a random spatial distribution. Nevertheless, for soils subjected to piping erosion, nonhomogeneous fabric would be generated as a *piping plane* in the form of localized discontinuous macropores. With the piping-induced void chains being predominantly oriented in the direction of the removed particles, the loss of contact with adjacent particles and the change in force chains inside the soil will induce variations in the mechanical response to the applied force. It can be imagined that such a change in fabric is very sensitive to the rotation of the major principal stress. However, to our knowledge,