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Numerical simulations of triaxial shearing-infiltration tests

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Abstract

The failure of steep slopes during rainfall is commonly associated with a decrease in matric suction in the unsaturated soil zone above the water table. The shear strength characteristics of residual soil under water infiltration have been studied in the laboratory using unsaturated triaxial tests. This paper presents a development of a numerical model for simulating a triaxial shearing-infiltration test to investigate the shear strength characteristics of a compacted kaolin under infiltration condition. Both the hydraulic and mechanical responses of the compacted kaolin are modeled using the commercial software SIGMA/W and in-house software YS-Slope. The numerical analyses result and their validation against laboratory test results are presented and discussed in this paper. The results from the numerical analyses show good agreements with those from the laboratory tests, indicating that the proposed numerical model can be used to simulate the triaxial shearing-infiltration tests in laboratory.
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Keywords: Numerical simulation; Shearing-infiltration; Triaxial test; Matric suction; Unsaturated soil

1. Introduction

Residual soils are commonly found in tropical regions. A deep groundwater table and a significant thickness of unsaturated zone above groundwater table are general characteristics of steep residual soil slopes. Many residual soil slopes remain stable due to the presence of matric suction within the unsaturated zone because it contributes additional shear strength to the soil and factor of safety to the slope. During rainfall, as water infiltrates into the slope, the pore-water pressure in the slope increases (matric suction decreases) and the additional shear strength due to matric suction either decreases or even disappears, causing the slope to be more susceptible to failure. To investigate slope stability during rainfall, an understanding of the relationship between shear strength characteristics and water infiltration is essential.

Many laboratory tests have been carried out to study the failure mechanism of unsaturated soil slopes due to the rainfall infiltration (Brand, 1981; Alonso et al., 1990; Yoshida et al., 1991; Fredlund and Rahardjo, 1993; Lim, 1995; Muraleetharan and Granger, 1999). However, the difficulties in selecting an appropriate testing method for matric suction measurements in laboratory tests have been problematic with regard to the collection of reliable and reproducible data. Several research works have been carried out to investigate the shear strength of soils under infiltration conditions. Wong et al. (2001) developed a triaxial apparatus for performing a shearing-infiltration test on soils under both saturated and unsaturated conditions. They concluded that the increase in pore-water pressure or decrease in matric suction caused the soil specimens to fail during the infiltration process. Melinda et al. (2004) conducted direct shear tests under shearing-infiltration conditions to investigate the shear strength characteristics

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of a residual soil during infiltration. The shearing-infiltration test results indicated that the matric suction decreased with an increase in the displacement rate of the soil specimen. They also found that a rapid reduction in matric suction is accompanied by a small soil displacement at the initial part of the infiltration stage. The soil displacement accelerated when failure of the soil was imminent. Meilani et al. (2005), Rahardjo et al. (2009), and Gui and Wu (2014) conducted triaxial shearing-infiltration tests to study the shear strength characteristics of saturated and unsaturated soils under infiltration condition. They proposed a failure envelope of a compacted soil from the results of the shearing-infiltration tests. Past research works focused only on experimental works of shearing-infiltration tests. There was no study carried out on the development of numerical model for simulations of triaxial shearing-infiltration tests.

This paper presents a numerical model to simulate the shear strength characteristics of compacted kaolin under infiltration condition during a triaxial shearing-infiltration test. Both hydraulic and mechanical responses of the soil are modeled using the commercial software SIGMA/W and in-house software YS-Slope. The results from the numerical analyses are directly compared with the corresponding laboratory test results.

2. Literature review

A triaxial test is commonly used to determine the stress-strain behavior of disturbed or undisturbed soils. The validation of constitutive models is carried out based on the soil behavior observed during the laboratory tests. Several researchers have carried out numerical analyses using the finite element method to develop the constitutive relationships for different types of material, which depend on several factors, i.e., the homogeneity, isotropy, and continuity of the materials (Desai and Christian, 1977; Carter, 1982; Chen and Baladi, 1985). These numerical analyses were normally performed in an axisymmetric and plane strain condition. The initial conditions in each of the models corresponded to the end of an isotropic consolidation. Some researchers employed the modified Cam-Clay model (Borja et al., 1997; Sheng et al., 1997) while others adopted linear elastic and perfectly plastic models (Schanz and Gussman, 1994) in their analyses. Recently, Fattah et al. (2011) performed the numerical simulation of triaxial test in clayey soil using four different constitutive models (e.g., linear elastic, Mohr-Coulomb, Modified Cam Clay, Cap model). These analyses concentrated on the conventional triaxial compression test because the shear strength under saturated conditions is commonly used for design purposes. No numerical models have been developed to simulate the shearing-infiltration test using a triaxial cell.

Shearing-infiltration tests have been conducted on residual soils from the Bukit Timah Granitic Formation (Han, 1997; Melinda, 1998; Wong et al., 2001) and Briones Hills field site (Anderson and Riemer, 1995) in Singapore. Based on these experimental studies, failure could be considered to have occurred during the shearing-infiltration tests when the deviator stress started to decline, or the strain rate started to increase excessively.

Recently, many numerical studies have been carried out to investigate the hydraulic response of unsaturated soils against rainfall infiltration. The uncoupled numerical analysis can be performed using the finite element software, SEEP/W. Hydraulic properties of soil (i.e., SWCC and permeability function) must be incorporated in SEEP/W for performing seepage analysis. On the other hand, the hydro-mechanical behavior of an unsaturated soil can be analyzed using the finite element software, SIGMA/W to obtain pore-water pressure distributions within soil layer and soil displacement during dry and rainy periods (Wong et al., 1998).

Some researchers have also developed a coupled hydro-mechanical finite element model, where the volume change of unsaturated soils is included in the analysis (Cho and Lee, 2001; Zhang et al., 2005; Kohgo et al., 2007; Borja et al., 2012; Kim et al., 2012). These coupled hydro-mechanical models were developed based on different constitutive models and stress state variables for describing the volume change behavior. The nonlinear elastic stress-strain relationship based on two stress state variables were employed by Cho and Lee (2001) and Zhang et al. (2005), while the elasto-plastic model considering the plastic strain based on the effective stress principle has been used by Borja et al. (2012) and Kim et al. (2012). In addition, Kim et al. (2016) developed a fully coupled analysis software (called YS-Slope) for unsaturated porous media by incorporating hydraulic and mechanical properties.

3. Methodology

3.1. Soil properties

The compacted kaolin used in this study was obtained from Kaolin Malaysia SDN BHD in Malaysia. The soil has a grain-size distribution of 85% silt and 15% clay-size particles (finer than 2 μm). The liquid limit, plastic limit, and plasticity index of the soil are 51.0, 35.6 and 15.4, respectively. According to the Unified Soil Classification System, USCS (ASTM D2487-00, 2000), the soil can be classified as a silt with high plasticity (MH). The specific gravity of the soil is 2.65, which was measured in accordance with ASTM D854-02 (2002). Soil specimens for the triaxial tests were statically compacted to the maximum dry density, $\rho_{\max}$, of 1.35 Mg/m^3 at 22% optimum water content, w_{opt} (Rahardjo et al., 2009). Standard Proctor compaction curve of the soil specimen is presented in Fig. 1. In the triaxial test, a compression machine with a fixed displacement rate of 1 mm/min was used to obtain a soil specimen with a diameter of 50 mm and a height of 100 mm. The saturated permeability, k_s, was measured using the rigid-wall permeability test in accordance with

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