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Failure of soil under water infiltration condition

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ABSTRACT

To reduce and mitigate rainfall-induced landslide problems, there is a need to improve our understanding of the failure mechanism of soil under water-infiltration condition. This study aimed at understanding the effect of water-infiltration on the transformation of shear stress and its eventual failure in unsaturated soil. The method of study was via a series of advanced laboratory triaxial test of two specific types: (1) constant-suction shearing test, and (2) shearing-infiltration test. The shearing-infiltration test results indicated that infiltration of water reduced the matric suction of the soil by the generation of excess pore-water pressure; it however was not accompanied by a reduction in shear strength, instead, the unsaturated soil failed under a constant shear stress applied prior to the infiltration. Excessive deformation and the eventual softening of the soil were found to be the main causes of water-infiltration induced failure.

1. Introduction

Rainfall has been recognized as one of the main causes of landslides in many tropical countries. For example, Taiwan suffers from landslides of various scales every year between the months of May and October as a result of the four to five intense typhoons that strike the island annually. According to studies conducted by the Public Construction Commission (Gui et al., 2008), there were about 1567 and 1718 rainfall-induced roadside (excluding expressway) landslides in Taiwan in 2004 and 2005, respectively; and the cost of reconstruction was roughly NTD3.53 billion in 2004 and NTD2.47 billion in 2005. When expressway landslides are included, the total number and cost of reconstruction for the whole island every year is much greater than the above figures. It has been widely claimed that during rainfall, increased water content in the soil decreases the soil suction above the ground water table and, thus, the shear strength of the soil. Water infiltration can lower the shear strength to a value close to the average shear stress along a potential failure surface and consequently trigger a landslide.

In many tropical regions the hot and humid weather coupled with high annual rainfall have resulted in rapid weathering of rock formation and development of a deep overburden of unsaturated residual soils (Han, 1997). Collins and Znidarcic (2004), Zhang et al. (2005), Huang and Yuin (2010), etc. have experimentally investigated the mechanism of rainfall-induced slope failures. Lee et al. (2011) conducted two types of instrumented laboratory tests, i.e. one-dimensional soil column and two-dimensional slope model tests, to examine the variations of suction in an unsaturated soil under certain rainfall conditions. The triggering phase of rainfall-induced landslides in coarse-grained soils was studied by Sorbino and Nicotera (2013). They observed that landslides are frequently related to rainfall events that significantly reduce matric suction in the shallower soil layers. Godt et al. (2012) proposed a numerical framework for assessing the stability of infinite slopes under transient variably saturated conditions; the framework includes profiles of pressure head and volumetric water content combined with a general effective stress for slope stability analysis, which could provide a way to quantify stress changes due to rainfall and infiltration relevant to shallow landslide initiation. Thus, it is important to understand the evolution of soil shear stress changes due to water infiltration as this knowledge is not only indispensable for slope stability analysis but some of the results may also be applicable to improve the current design methodology and improve slope maintenance work.

The behavior of a soil with a known initial state, a boundary condition and a loading type because of any mechanical process, can be studied experimentally via the triaxial test (Terzaghi and Peck, 1967; Bishop and Henkel, 1969). Triaxial tests on unsaturated soils were usually conducted under various net normal stresses and matric suctions (see for example, Kim and Kim, 2010). However, the stress path followed by a soil element that undergoes water infiltration and subsequent failure in a slope is seldom modeled in laboratory testing. It is important to perform tests following the appropriate field stress path to characterize the failure mechanism of rain-induced slope failure

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as well as to determine the strength envelope of soil. Melinda et al. (2004) investigated the strength and deformation characteristics of a re-compacted residual soil during infiltration using two modified direct shear apparatuses. They suggested that slope failure was associated to the reduction of suction in the soil; however, the tests were conducted in a shear box device that had a pre-determined failure plane, which is the interface of the two halves of the shear box. To verify the volume change theory for unsaturated soil, Meilani et al. (2005) conducted triaxial tests to study the pore-water pressure and water volume change of re-compacted coarse kaolin under infiltration conditions. Both studies used re-compacted soils and, to guarantee failure, these tests were conducted at a very high stress level (i.e. about 85–90% of the soil's shear strength). The shear strength and the response of the pore-water pressure in real intact soil, which has its in situ micro-structure unaltered, under water-infiltration process are however still unknown.

Detailed and fundamental studies of the evolution of shear stress due to water infiltration of intact residual soil, which is commonly found in many tropical countries, have seldom been performed in laboratory testing, and it has not been verified whether the shear strength under a water infiltration process was similar to the shear strength under a constant suction condition. The main aim of this study is to evaluate the mechanical behavior and failure mechanism of residual soil as a result of water infiltration via a series of laboratory triaxial tests. The evolution of the shear stress changes in the soil during the infiltration process is also studied. In addition, the study tries to offer an answer to the question that is often raised by engineers:

> Since most of the unsaturated soil slopes were designed using the shear strength parameters of saturated soil, why has failure still occurred on many unsaturated soil slopes especially after a period of rainfall even though their remaining shear strength was still higher than that of the saturated soil slopes?

2. Material studied

The soil used in this study was obtained from Linkou terrace, which is situated in the northwest of Taiwan. The top formation of the terrace is a 5–15 m thick brick-red lateritic soil (Chen and Yang, 1987; Chen and Liu, 1993; Bruce et al., 2006). The soil was the product of both chemical and physical weathering, which involved varying degrees of wind, an average annual temperature of 20–25 °C and a minimum annual rainfall of 750 mm, on cobbles.

The study site was located at the center of the terrace with an elevation of about 251 m above sea level with a groundwater table at about 10 m or deeper below the ground surface. Soil specimens of 5.6 cm diameter by 30 cm long were obtained from trial pits of various depths. As groundwater table was not encountered at these depths, thus, the soil was in an unsaturated condition with an average in situ degree of saturation of about 85%. The shear strength and the permeability of unsaturated lateritic soil at nearby sites have been studied by Gui and Yu (2008) and Gui and Hsu (2009), respectively. In addition, the soil also showed high potential for shrinking and swelling due to water content changes (Gui and Chu, 2005).

2.1. Soil physical properties

A series of soil physical property tests were conducted by Gui and Wu (2011), and Wu (2011) to determine the soil water content (ASTM D2216-10, 2010), specific gravity (ASTM D854-10, 2010), particle size distribution (ASTM D422-63, 2002), liquid limit and plastic limit (ASTM D4318-10, 2010) of the study soil.

The initial water content of the soil ranged between 26.2% and 30.6%; the average specific gravity was 2.718 with a standard deviation of 0.027; while the average void ratio was 0.889 with a standard deviation of 0.042. The particle size distribution curves obtained are shown in Fig. 1a, which shows that the soil was composed of 12.2% sand, 86.8% silt and 1% clay; it thus has more than 50% of silt-sized particles. Atterberg limits test was carried out on soil passing through sieve No. 40. The liquid limit (LL) of the study soil ranged between 40.6% and 47.7%, the plastic limit (PL) ranged between 24.6% and 32.4%; thus its plasticity index (PI) ranged between 12.5% and 20.0% (Figure 1b). According to the Unified Soil Classification System (USCS), the soil should be classified as low plasticity clay/silt (CL/ML).

2.2. Soil water characteristic curve

Soil water characteristic curve (SWCC), also referred to as the soil moisture retention curve, depicts the relationship between soil volumetric water content and matric suction (Zhai and Rahardjo, 2012). It is an important relationship that shows the ability of an unsaturated soil to retain water under various matric suctions and, thus, has a similar role as the consolidation curve of a saturated soil that relates void ratio to effective stress (Fredlund and Rahardjo, 1993). A complete SWCC could be categorized into three suction ranges: low suction ranges between 0 kPa and 100 kPa; medium suction ranges between 100 kPa and 1500 kPa; and high suction ranges between 1500 kPa and 1,000,000 kPa. The SWCC is commonly obtained using the pressure plate extractor (for low and medium suction ranges) and salt solutions method (for high suction range). In this study, the pressure plate extractor test was conducted in accordance with ASTM D6836-02 (2007) and the salt solutions method was conducted in accordance with ASTM D5298-03 (2003).

Fig. 2 shows the SWCC result of the study soil performed following a drying path on specimens of different void ratios via the pressure plate extractor and salt solutions method. The maximum matric suction measured in the pressure plate extractor and the salt solutions method

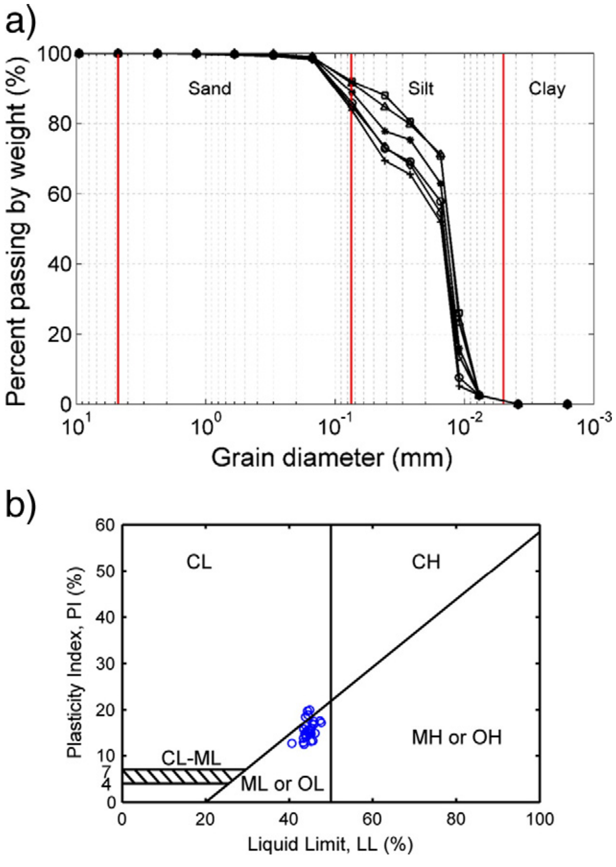

Fig. 1. (a) Particle size distribution; and (b) classification of the study soil.