Applied Clay Science 50 (2010) 386–394

Contents lists available at ScienceDirect

Applied Clay Science

journal homepage: www.elsevier.com/locate/clay

Centrifuge modelling of clay slope with montmorillonite weak layer under rainfall conditions

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ARTICLE INFO

Article history:
Received 14 December 2009
Received in revised form 31 August 2010
Accepted 2 September 2010
Available online 15 September 2010

Keywords:
Centrifuge modelling
Clay
Slope
Weak layer
Rainfall
Infiltration

ABSTRACT

Rainfall is a major triggering factor for the failure of soil slopes, and weak layers, which can be commonly found within slopes, tend to act unfavourably upon slope stability. A series of centrifuge model tests was conducted to investigate the behaviour of clay slopes with highly permeable weak layers during rainfall. In addition, homogeneous slopes were also considered in the model tests as a comparison. The horizontal weak layers within the slopes were composed of a mixture of montmorillonite and filter paper scraps to obtain high permeability and compressibility due to saturation. Observations showed that the weak layers caused rainfall to infiltrate deeper in weak-layered slopes compared with the homogeneous slopes, which resulted in an additional displacement. On the other hand, the deformation of the weak layer itself also contributed to the additional displacement. Shear zones appeared in the slopes during rainfall, which became discontinuous at weak layers. The shear zones widened initially due to the development of deformation, but as rainfall persisted, they localized swiftly, leading to the failure of clay slopes.

1. Introduction

Slope failures account for the loss of countless lives around the world, and cause significant economical loss (e.g. Chen et al., 2004; Ochiai et al., 2004; Montrasio et al., 2009). It is widely acknowledged that rainfall acts as a major triggering factor in the failure of soil slopes. Hence, it becomes an issue of great importance to analyse stability levels of slopes under rainfall conditions. Unfortunately, the complicated mechanisms and various influencing factors concerned make rainfall-induced slope failure a difficult problem to tackle. Significantly, weak layers, which can be commonly found within slopes, could induce or accelerate the failure of slopes (e.g. Al-Homoud and Tubeileh, 1998; Goh, 1999).

The responses of soil slopes during rainfall have been investigated using different approaches, including field studies, model tests, and numerical/analytical analysis. Field studies (e.g. Lim et al., 1996; Rahardjo et al., 2005; Zhan et al., 2007; Trandafir et al., 2008) have pointed out that the failure mechanism exhibits a close relationship with decrease in soil shear strength due to the reduction in matric suction. Though field tests can provide first hand observations, they are often very time-consuming and highly expensive, and control of boundary conditions is hard to achieve. Using small-scale model tests, Tohari et al. (2007) discussed failure initiation and failure modes in slopes under rainfall, coming to the conclusion that most rainfall-induced slopes fail with a shallow noncircular slip surface. However, as small-scale models are generally accepted to be not fully capable of simulating actual slope behaviours due to the difference in stress levels between the model and prototype, full size modelling (e.g. Moriwaki et al., 2004) and centrifuge modelling (e.g. Kimura et al., 1991; Take et al., 2004; Hudacsek et al., 2009) have been widely used in rainfall-induced slope failure tests. Centrifuge modelling provides a method to achieve similar stress levels with relatively small models through increased acceleration fields (Schofield, 1980; Viswanadham and Rajesh, 2009). For example, Take et al. (2004) used misting nozzles to simulate rainfall in centrifuge models and performed a series of tests to study the landslide mechanism of unsaturated soil slopes. Through numerical studies, a diverse range of mathematical models have been developed to analyse the stability and to predict the failure of slopes under rainfall (e.g. Iverson, 2000; Ng et al., 2001; Tsaparas et al., 2002).

While most previous studies have looked into the failure modes and mechanisms of homogeneous slopes during rainfall, the more complicated and dangerous case of slopes with weak layers should not be neglected. A few studies on the effect of the weak layers have been conducted by using numerical analysis. For example, Goh (1999) used a genetic search algorithm to determine the critical slip surface in non-homogeneous soil slopes with thin, weak layers. Urciuoli et al. (2007) analysed local failures before general slope failure along weak layers. In addition, case studies have been carried out on cut slopes in Jordan, concluding that slide movements always coincided with weak layers (Al-Homoud and Tubeileh, 1998).

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doi:10.1016/j.clay.2010.09.002

Through centrifuge model tests of clay slopes with weak layers, this paper focuses on the behaviour of slopes with highly permeable weak layers under rainfall conditions. The objectives of this study are: (1) to simulate and observe the deformation process of slopes with weak layers under rainfall conditions, (2) to investigate the effect of highly permeable weak layers on rainfall infiltration and displacement of clay slopes, (3) to discuss the formation of shear zones during rainfall and its relationship with the failure of slopes.

2. Experimental methodology

2.1. Test configurations

Three heterogeneous slopes with weak layers were considered in the tests, and the homogeneous slope (H) was mainly used for a comparison to discuss the effect of weak layers. The heterogeneous slopes each consisted of highly permeable water softening layers placed at different locations, in the top 1/3 or bottom 1/3 of the slopes (Fig. 1). The three heterogeneous slopes included an upper weak-layered slope (UW), a lower weak-layered slope (LW) and a double weak-layered slope (DW). As a result, the effect of the weak layer's positions can be studied. The slope profiles are summarized in Table 1.

Fig. 1 shows the profiles of model slopes. The slopes were constructed to have a slope angle of 45° and a height of 300 mm, with a slope top width of 140 mm. The base of the slope was 60 mm thick. The weak layers in the slopes were 20 mm thick. A rectangular Cartesian coordinate system (Fig. 1(a)) was set for the convenience of analysis; in this coordinate system the top and bottom of the slope were at $y = 0$ mm and $y = 300$ mm respectively, and the weak layers were positioned at $y = 110$ mm and $y = 200$ mm.

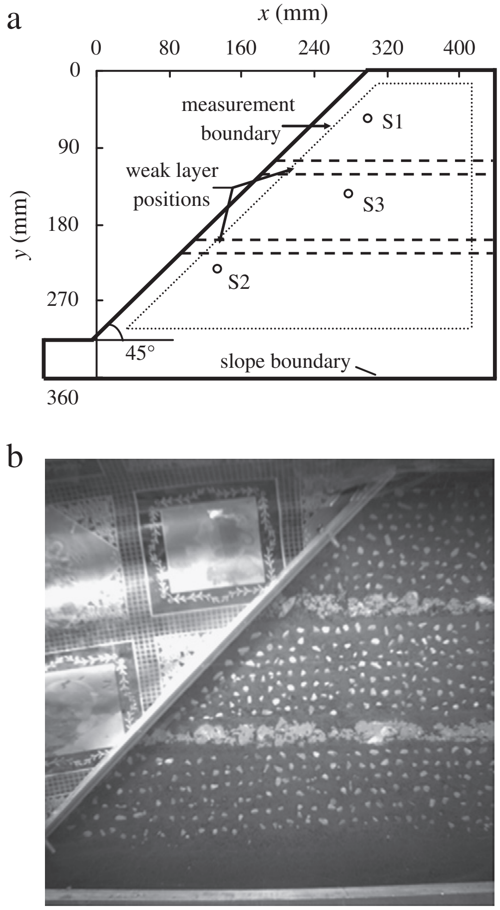

Fig. 1. Experimental profile of double weak-layered slope: (a) schematic view; (b) photographic view.

Table 1
Profiles of model slope.

Model slope	Weak layer position
Homogeneous (H)	–
Upper weak-layered (UWS)	$y = 110$ mm
Lower weak-layered (LWS)	$y = 200$ mm
Double weak-layered (DWS)	$y = 110$ mm and $y = 200$ mm

2.2. Materials

The cohesive soil used in tests was acquired from a subway station in Beijing, China. The soil has a specific gravity of 2.71. The effective particle size (D_{10}) and uniformity coefficient (D_{60}/D_{10}) of the soil are 0.003 mm and 16.7, respectively. The maximum dry density, gained through a standard Proctor test, is 1.803 g/cm^3 at an optimum moisture content of 16%. The plastic and liquid limits of the soil are 15% and 28%, respectively; the plastic index is 13. This soil can be classified as CL according to Unified Soil Classification System (UCSC). Fig. 2 shows the soil–water characteristic curve of the soil, which was measured by using the UMS T5 tensiometer. It can be seen that soil suction decreases as moisture content increases under a monotonic saturation process. The initial soil moisture and dry density of the experimental slopes were controlled to (17.8 ± 0.4) % and (1.50 ± 0.02) g/cm^3, respectively. The permeability of the soil was 2.5×10^{-5} cm/s at this dry density under saturation condition.

The weak layers in natural slopes are generally softer than the rest of the slope and significantly change the rainfall infiltration patterns. As natural weak layer materials are difficult to obtain, the weak layers in the tests were simulated using montmorillonite powder that was mixed with fine filter paper scraps. Montmorillonite exhibits significant softening due to saturation, which makes it an ideal material for weak layer simulation. To obtain high permeability without increasing its strength, fine qualitative filter paper scraps were added into the montmorillonite. The weight ratio between filter paper scraps and montmorillonite was set to 1:50. The plastic limit and liquid limit of the mixed material are 30% and 54%, respectively; the plastic index is 24. The material can be classified as CH, which is clay of high plasticity. The weak layer's initial moisture was (45 ± 0.5) % and it had a dry density of (1.10 ± 0.02) g/cm^3. Under saturated condition with such a dry density, the coefficient of permeability of the mixed material was 1.5×10^{-4} cm/s, the shear strength parameters were 12 kPa in cohesion and 18° in the internal frictional angle. It can be seen that the shear strength of the mixed material was fairly small. The compressibility of the mixed material was also significantly greater than that of the cohesive soil.

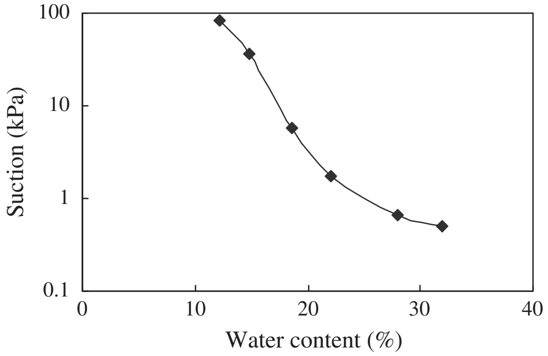

Fig. 2. Soil–water characteristic curve of soil.