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Centrifuge modeling of the geotextile reinforced slope subject to drawdown

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A B S T R A C T

Geotextile is an effective reinforcement approach of slopes that experiences various loads such as drawdown. The geotextile reinforcement mechanism is essential to effectively evaluate the safety of geotextile-reinforced slopes under drawdown conditions. A series of drawdown centrifuge model tests were performed to investigate the deformation and failure behaviors of slopes reinforced with different geotextile layouts. The deformation and failure of unreinforced and reinforced slopes were compared and the geotextile reinforcement was indicated to significantly increase the safety limit and the ductility, reduce the displacement, and change the failure feature of slopes under drawdown conditions. The slopes exhibited remarkable progressive failure, downward from the slope top, under drawdown conditions. The progressive failure was induced by coupling of deformation localization and local failure based on full-field measurements of displacement of slopes subjected to drawdown. The geotextile reinforced the slope by decreasing and uniformizing the slope deformation by the soil-geotextile interaction. Through geotextile displacement analysis, the geotextile-reinforced slope was divided into the *anchoring zone* and the *restricting zone* by a boundary that was independent of the decrease of water level. The geotextile restrained the soil in the *anchoring zone* and the soil restrained the geotextile in the *restricting zone*. The reinforcement effect was distinct only when the geotextile was long enough to cross the slip surface of the unreinforced slope under drawdown conditions.

1. Introduction

In practice, slopes often experience significant increases and decreases in water level due to a diverse range of causes such as rainfall, tides, and the operation of large reservoirs. Many landslides are induced by drawdown (Pamuk et al., 2015). For example, a large-scale landslide occurred due to the water variation in the Three Gorges reservoir on July 14, 2003 and resulted in 24 deaths and huge property loss (Jian et al., 2014).

Geotextiles have proved to be an effective reinforcement approach for unstable slopes under various conditions (Wang et al., 2011). As geotextiles are widely used to increase the stability of slopes, there is a need to analyze accurately the reinforcement effect of geotextiles on slopes under drawdown conditions.

Geotextile reinforcement is often simplified to an equivalent force on the slope. With this assumption, limit equilibrium and limit analysis methods were modified for the stability analysis of geosynthetic-reinforced slopes (Srbulov, 2001; Gao et al., 2016). Rigorous numerical methods, such as finite element methods, were employed to examine geotextile reinforcement behavior and overall slope stability (Mehdipour et al., 2013; Huang, 2014; Bhattacherjee and Viswanadham, 2015; Thuo et al., 2015). A diverse range of unreinforced slope cases were analyzed using numerical limit equilibrium methods (Ozer and Bromwell, 2012; Gao et al., 2014; Liang et al., 2015; Zhang and Luo, 2017), limit analysis methods and finite element methods with seepage analysis (Vandamme and Zou, 2013; Jian et al., 2014; Stark et al., 2014, 2017). However, drawdown conditions have not been carefully considered in these numerical studies of geotextile reinforced slopes. Numerical methods depend on reasonable models of the soil and the soil-geotextile interface investigated using laboratory tests and discrete element methods (Zhang and Zhang, 2009; Cheng et al., 2016). The existing stability analysis methods have not reasonably captured the progressive failure of slopes under drawdown conditions (Luo and Zhang, 2016).

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Field observations and model tests provide an effective approach to investigate the slope failure mechanism. Field observations were widely used to examine geotextile reinforcement behavior and the drawdown-induced failure of slopes (Indraratna et al., 2010; Kaunda, 2010; Ozer and Bromwell, 2012; Portelinha et al., 2013; Piccinini et al., 2014). For example, the geosynthetic reinforcement significantly increased the aseismic stability of slopes according to post earthquake investigations (Sandri, 1997).

The geotextile reinforcement behavior and the drawdown-induced response of slopes were discovered via a number of 1 g model tests (Jia et al., 2009; Chen et al., 2012; Srilatha et al., 2012; Wang et al., 2012; Akay et al., 2013; Palmeira and Tatto, 2014; Turker et al., 2014; Mehrjardi et al., 2016). Centrifuge model tests provide a more appropriate approach for the study of slope behavior because they can reproduce the equivalent stress level in a small-scale model with a prototype. The geotextile reinforcement effect of slopes was investigated using centrifuge model tests under various conditions (Hu et al., 2010; Wang et al., 2011; Rajabian et al., 2012; Yang et al., 2012; Costa et al., 2016; Rajabian and Viswanadham, 2016). Several centrifuge model tests were conducted on hybrid geosynthetic reinforced slopes, and the observations confirmed that the geosynthetics could increase the stability level of low permeability slopes under impoundment conditions (Raisinghani and Viswanadham, 2011). Drawdown induced a significant coupling process of local failure and deformation localization in the slope according to observations from a series of centrifuge model tests (Luo and Zhang, 2016). Few results have been presented to show the geotextile reinforcement effect and mechanism that plays an essential role in the analysis of stability of geotextile-reinforced slopes under drawdown conditions.

This paper presents a series of centrifuge model tests performed to investigate the behavior of geotextile-reinforced slopes during drawdown. The deformation and failure behaviors of unreinforced slopes and slopes reinforced with different geotextile layouts were compared to analyze the reinforcement effect and influencing factors. The progressive failure mechanism of geotextile-reinforced slopes was examined by an integrated analysis of deformation and failure processes using full-field measurements of the displacement of slopes subjected to drawdown. The geotextile reinforcement mechanism was clarified by systematic analysis of geotextile-performance, slope failure mechanism, and soil-geotextile interaction. The reinforcement mechanism explains how the geotextile increases the stability of slopes and is a reference for a reasonable design of geotextile reinforcement under drawdown conditions.

2. Test set-up

2.1. Devices

The centrifuge model tests were conducted on a 50 g-ton geotechnical centrifuge with a maximum acceleration of 250 g. An in-flight water simulator was installed on the centrifuge to realize water impoundment, drawdown and real-time water level measurement in a centrifuge model test (Luo and Zhang, 2016).

The model container for the tests, made of aluminum alloy, was 60 cm long, 20 cm wide and 50 cm high. A transparent glass was installed on the long lateral side of the container in order to observe the deformation and failure processes of the model slope.

2.2. Model preparation

According to the similarity criterion for the centrifuge model tests, the length, displacement, thickness and water level of the prototype are n times those of the model when the centrifugal acceleration is n g. The strain and the modulus of the prototype are equal to those of the model. The time of the prototype is n^2 times that of the model at n g-level if the water infiltration in the slope is mainly driven by gravity (Zhang et al., 2011). Accordingly, the drawdown rate of the prototype is $1/n$ times that of the model. However, the time ratio in centrifuge model tests may be more complicated due to the suction of cohesive soil and requires further investigation.

A cohesive soil with a plastic limit of 18.5% and a liquid limit of 25% was used for the model slope. This soil was CL-ML according to the USCS classification. The specific gravity of the soil was 2.7. The average soil particle size of the soil was 0.06 mm, and d_{60} and d_{10} particle sizes were 0.075 mm and 0.015 mm, respectively.

The soil was compacted by 5-cm-thick soil layers to reach the designed dry density of 1.55 g/cm^3 and the water content was controlled at 18% for all the tests. The gradient of all the model slopes was 1:1 by cutting down redundant soil (Fig. 1). The height of

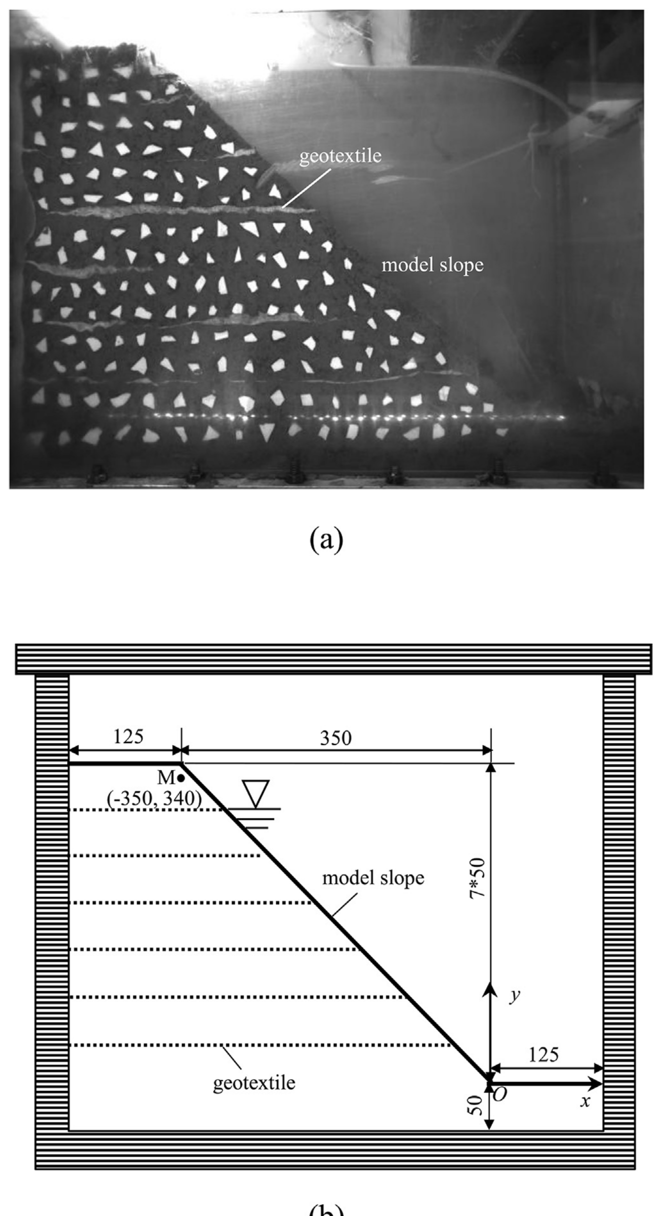

Fig. 1. Schematic view of the slope model reinforced with full geotextile. (a) Photograph; (b) structural view (unit: mm).