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Centrifuge model tests of geotextile-reinforced soil embankments during an earthquake

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ABSTRACT

The behavior of geotextile-reinforced embankments during an earthquake was investigated using centrifuge model tests, considering a variety of factors such as gradient of slope, water content of soil, geotextile spacing, and input shaking wave. The geotextile-reinforcement mechanism was revealed on the basis of the observations with comparison of the unreinforced embankment. The geotextile significantly decreases the deformation of the embankment and restricts sliding failure that occurs in the unreinforced embankment during an earthquake. The displacement exhibits an evidently irreversible accumulation with a fluctuation during the earthquake which is significantly dependent on the magnitude of input shaking. The peak strain of the geotextile exhibits a nearly triangular distribution in the vertical direction. The embankment can be divided into two zones, a *restricting zone* and *restricted zone*, where the soil and geotextile, respectively, play an active restriction role in the soil-geotextile interaction. The soil restricts the geotextile in the *restricting zone*, and this restriction is transferred to the *restricted zone* through the geotextile. The strain magnitude of the geotextile and the horizontal displacement of the geotextile-reinforced embankment decrease with increasing geotextile layers, with decreasing water content of the soil, with decreasing gradient of the slope, and with decreasing amplitude of the earthquake wave.

1. Introduction

Geotextiles are an effective reinforcement for various soil structures such as slopes and containing walls (e.g., Schaefer, 1997). In recent years, geotextile has been used to increase the seismic stability level of a large quantity of small-size and medium-size earth embankments, which can be regarded as a kind of typical slope.

Field observation is an essential approach to obtain first-hand data for analyzing the behavior of the geotextile-reinforced slopes/embankments. For example, eleven reinforced soil structures were visually examined for evidence of distress resulting from an earthquake, and the results showed that these structures exhibited excellent seismic stability (Sandri, 1997). The seismic stability of an old earth-fill dam in Japan was significantly increased by constructing a counter-balance fill using geosynthetic reinforcement (Tatsuoka et al., 2007). A large number of field surveys were conducted on geosynthetic-reinforced embankments, and valuable understanding was obtained (e.g., Kelln et al., 2007; Indraratna et al., 2010). Nevertheless, the field observation cannot easily change the boundary conditions or loading styles, which means that this approach cannot be used in an investigation of the geosynthetic-reinforcement mechanism. The proper geosynthetic design of slopes/embankments is largely dependent upon systematic understanding of the behavior of such reinforced soil structures, which can be investigated by numerical simulations and model tests.

The limit equilibrium methods, which have been accepted in many engineering codes, were widely employed to evaluate the stability level of geosynthetic-reinforced slopes/embankments (e.g., Srbulov, 2001). A set of equations were formulated to determine the seismic stability and permanent displacement of cover soil in a solid-waste containment system (Ling and Leshchinsky, 1997). Diverse types of analysis methods, including theoretical and numerical methods, were used to investigate the behavior and influence parameters of the overall stability level of reinforced soil structures (e.g., Sawicki and Lesniewska, 1991; Qhaderi et al., 2005; Shukla and Kumar, 2008; Abusharar et al., 2009; Tolooiyan et al., 2009). The reliability analysis was also introduced to the safety assessment of reinforced soil structures (Genske et al., 1991). The effectiveness of numerical analysis is significantly dependent on the accurate modeling of the soil–geosynthetic interface, which has been investigated using a number of laboratory tests (e.g., Wu et al., 2008; Zhang and Zhang, 2009; Zhang et al., 2010).

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The model tests offer a powerful approach to investigate the behavior and failure mechanism of reinforced soil structures under earthquake conditions by considering various factors with efficiency. For example, shaking table tests were performed on six geosynthetic-reinforced soil retaining wall models, and the results were used to analyze the effectiveness of a pseudo-static seismic stability analysis (Matsuo et al., 1998). Centrifuge model tests play an important role in such a research category as they have the advantage of reproducing the same stress level, similar deformation and failure mechanism as presented in a prototype. A series of centrifuge tests were conducted to investigate the failure mechanism, and a new distribution reinforcement force was proposed (Zornberg et al., 1998). Dynamic centrifuge tests were used to demonstrate that the earthquake loading has a significant effect on the tension experienced by the geomembrane on a landfill slope (Thusyanthan et al., 2007). A diverse range of centrifuge model tests were also conducted on the reinforced slopes with different reinforcement structures, such as geotextiles and soil nails (e.g., Porbaha and Goodings, 1996; Chen et al., 2007; Viswanadham and König, 2009; Hu et al., 2010; Wang et al., 2010). However, few results were reported using this type of test on the research of behavior of geotextile-reinforced embankments during an earthquake.

The behavior of geotextile-reinforced embankments during an earthquake was investigated by using centrifuge model tests in this paper, considering different factors such as slope inclination, soil moisture, reinforcement layout, and input shaking wave. Apart from traditional investigations of dynamic response such as acceleration amplification, this paper focuses on full observations of earthquake-induced deformation of the embankments and accordingly reports an examination of the response of embankment, the performance of the geotextile, and the soil-geotextile interaction. Therefore, the geotextile-reinforcement mechanism was revealed to explain how the geotextile reduces the deformation and prevents the probable failure of the embankments. This explanation can help to establish a proper design of geotextile reinforcement under earthquake conditions. In addition, the influence characteristic of different factors on the dynamic behavior of the reinforced embankment was investigated based on the measurements of centrifuge model tests.

2. Tests

2.1. Devices

The 50 g-ton geotechnical centrifuge of Tsinghua University was used for the centrifuge model tests. A specially manufactured shake table was equipped on the centrifuge to generate horizontal earthquake waves via a complex hydraulic pressure servo-system.

The model container for the tests was made of aluminum alloy and was 50 cm long, 20 cm wide and 35 cm high. A transparent lucite window was installed on one container side, through which the deformation process of the soil could be observed and recorded.

2.2. Schemes

Table 1 lists the centrifuge model tests conducted in this paper. The primary centrifuge tests were conducted on the geotextile-reinforced (RP) and unreinforced embankments (UP), respectively, which were compared to investigate the behavior and reinforcement mechanism of the geotextile-reinforced embankments. In addition, a few comparative tests were conducted to discuss the effectiveness of the knowledge and the influence factors by altering several aspects based on the primary tests, including the gradient of the slope (RC1), the water content of the soil (RC2), the geotextile spacing (RC3), and the amplitude of the input earthquake wave (RC4), respectively.

Table 1
List of centrifuge model tests.

Case	Gradient of slope	Water content of soil	Geotextile spacing	Amplitude of shaking wave
Unreinforced-primary (UP)	1.5:1	17%	–	9.7 g
Reinforced-primary (RP)	1.5:1	17%	6 cm	9.7 g
Reinforced-comparative-1 (RC1)	3:1	17%	6 cm	9.7 g
Reinforced-comparative-2 (RC2)	1.5:1	12%	6 cm	9.7 g
Reinforced-comparative-3 (RC3)	1.5:1	17%	12 cm	9.7 g
Reinforced-comparative-4 (RC4)	1.5:1	17%	6 cm	6.5 g

2.3. Model

Fig. 1 shows the schematic view of the geotextile-reinforced model embankment for the primary test. The unreinforced embankment is identical except for removal of the geotextile. The soil was retrieved directly from the stratum of a forest park in Beijing, China, with a plastic limit and liquid limit of 5% and 18%, respectively. The specific gravity of the soil was 2.7. The average particle size (d_{50}), effective particle size (d_{10}), and control particle size (d_{60}) of the soil were 0.03 mm, 0.0012 mm, and 0.04 mm, respectively. The standard Proctor test results showed that the optimum water content of the soil was 15.2%, with a maximum dry density of 1.79 g/cm^3.

The model embankment was 25 cm in height for all the tests and a 6-cm-high horizontal soil layer under the embankment was set to diminish the influence of the bottom container plate on the deformation of the embankment. In addition, silicone oil, with kinematic viscosity of 500 cSt, was painted on both sides of the container to decrease the friction between the embankment and the container. The gradient of slope was 1.5:1 (Vertical: Horizontal) for the primary tests and increased to 3:1 for a comparison.

The water content of soil was 17% (corresponding maximum dry density: 1.68 g/cm^3) for the primary test and decreased to 12% (corresponding maximum dry density: 1.65 g/cm^3) for a comparison. The soil was compacted by 5 cm-thick layers into the container with a dry density of 1.45 g/cm^3 for both water contents. It should be noted that the dry density of the soil was selected to be smaller than the actual case to obtain a more significant deformation for a better analysis of the reinforcement rules.

The consolidated undrained cyclic triaxial tests were conducted on the unsaturated soil. Fig. 2 shows the shear modulus of the soil and the Poisson's ratio was taken as 0.3 by referring to the similar soils empirically. It can be seen that the peak to peak secant shear modulus decreased with increasing shear strain. The shear strength of the soil (water content: 17%) was 20 kPa in cohesion and 25° in the internal frictional angle, which was obtained under the condition that the axial strain reached 5%. The shear strength of the soil with a moisture content of 12% was somewhat larger.

A type of medical gauze with a thickness of 0.14 mm was used to simulate the geotextile of the reinforced embankment. The elastic modulus of this reinforcement material was 40 kN/m according to the strain-controlled tensile loading test with a strain rate of 0.1%/min (Fig. 3). According to similarity criterion (Table 2) (Ko, 1988), it can be shown that the gauze is a reasonable substitute of the geotextile prototype, which has a typical thickness from several mm with an elastic modulus of hundreds of kN/m at a centrifugal acceleration of 50 g. Four layers of geotextile were horizontally arranged with an equal spacing of 6 cm at different elevations throughout the embankment (Fig. 1), and two layers of geotextile (layers 2 and 4 in Fig. 1b) were used for a comparison (RC3).

2.4. Measurements

A series of accelerometers with a measurement accuracy of 0.3% was buried in the embankment to measure the acceleration response