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Study of dynamic stability of unsaturated embankments with different water contents by centrifugal model tests

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Abstract

It has been pointed out that the damage to unsaturated embankments caused by earthquakes is attributed to the high water content brought about by the seepage of underground water and/or rainfall infiltration. It is important to study the effects of the water content on the dynamic stability and deformation mode of unsaturated embankments in order to develop a proper design scheme, including effective reinforcements, for preventing severe damage. This paper presents a series of dynamic centrifugal model tests with different water contents to investigate the effect of the water content on the deformation and failure behaviors of unsaturated embankments. By measuring the displacement, the pore water pressure and the acceleration during dynamic loading, as well as the initial suction level, the dynamic behavior of unsaturated embankments with an approximately optimum water content, a higher than optimum water content, and a lower than optimum water content, are discussed. In addition, an image analysis reveals the displacement field and the distribution of strain in the embankment, by which the deformation mode of the embankment with the higher water content is clarified. It is found that in the case of the higher water content, the settlement of the crown is large mainly due to the volume compression underneath the crown, while the small confining pressure at the toe and near the slope surface induces large shear deformation with volume expansion.

Keywords: Unsaturated soil; Embankment; Centrifugal model test; Water content; Dynamic loading

1. Introduction

The seismic vulnerability of road embankments has been recognized as an important geotechnical problem. In past earthquakes, road embankments have experienced catastrophic failures. A recent example is the collapse of highway embankments caused by the 2011 off the Pacific Coast of Tohoku Earthquake on March 11, 2011. In addition, the road embankments constructed on the mountain/hill sides were severely damaged by the 2009 Suruga-bay Earthquake, the 2007 Noto Hanto Earthquake, and the 2004 Niigata-ken Chuetsu Earthquake (e.g., National Institute for Land and Infrastructure Management and Public Works Research Institute (NILIM and PWRI), 2004, 2011; National Institute for Land and Infrastructure Management, Public Works Research Institute and Building Research Institute (NILIM,

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PWRI and BRI), 2008; Central Nippon Expressway, Co. Ltd. 2009). The collapse of road embankments is a very important issue since the fragmentation of road transportation disables the supply of relief materials and the carrying of injured persons, and also induces the isolation of villages.

It has been pointed out that the road embankments severely damaged during these past earthquakes contained a great deal of water due to seepage water or rainfalls. In particular, embankments constructed on valley-like topographies are apt to allow underground water to flow into them. In the cases of the Noto Hanto Earthquake and the Niigata-ken Chuetsu Earthquake, the seepage water flow and the high water content are possible reasons for the damage (e.g., Sasaki et al., 2008). This suggests that the effect of the seepage water flow and the high water content in embankments on the dynamic failure of road embankments has to be studied in detail.

Recently, many researchers have tried to study the dynamic stability of unsaturated embankments by taking into account the water content history via centrifugal model tests (e.g., Hayashi et al., 2002; Matsuo et al., 2002; Ohkawa et al., 2008; Okamura et al., 2013). The aim of most of these studies has been to reveal the effect of the increase in water content on the amount of deformation. This is because the displacement, such as the settlement of the crown, is crucial for road embankments as an infrastructure in the engineering sense. It is important, however, to know the deformation modes of unsaturated embankments in order to properly evaluate the seismic stability and to propose effective reinforcement methods. From this point of view, and to the authors' knowledge, there has been only a limited number of such studies.

In addition, a physical interpretation of the dynamic behavior of unsaturated embankments has rarely been reported because the physical modelling of unsaturated soils is more complicated than that of fully saturated soils in terms of the similarity rules for suction and the distribution of water contents. There have been publications on static deformation and strength characteristics, including oedometric tests (Thorel et al., 2013) and capillary rises (Rezzoug et al., 2000; Esposito, 2000; Okamura and Tamamura, 2011) under centrifugal conditions. They have revealed that the suction level and the distribution of water contents in a prototype scale are almost independent of centrifugal acceleration. It is necessary, however, to study further the deformation and failure characteristics of unsaturated soils subjected to dynamic loading based on the findings obtained under static conditions.

In this study, dynamic centrifugal model tests on unsaturated road embankments with different water contents are conducted in order to clarify the relation between the dynamic stability of road embankments and the water content history of the embankments. Embankments are generally constructed by compaction with an approximately optimum or slightly higher than optimum water content. It is known that unsaturated embankments exhibit the highest strength with a slightly lower water content owing to the effect of suction. When the embankments are subjected to an increase in groundwater level and/or the infiltration of water from the surface, due to rainfalls or seepage flow, the water content of the embankments increases and the

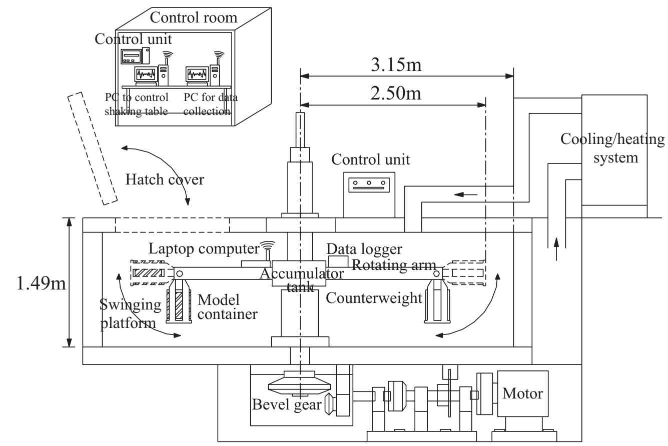

Fig. 1. Schematic figure of geotechnical centrifuge machine at DPRI, Kyoto University.

Table 1
Specifications of centrifugal model test machine.

Effective rotation radius	2.50 (m)
Effective space for model installation ($L \times W \times H$)	$800 \times 320 \times 800$ (mm)
Allowable weight of model	120 (kg)
Test capacity	24 (g/t)
Maximum centrifugal acceleration	200(g)

suction eventually decreases. The post-survey by Sasaki et al. (2008) on the 2007 Noto Hanto Earthquake provides that a higher water content due to the large fines content and higher levels of groundwater inside the embankments were observed in the largely deformed embankments. Hence, we have conducted tests with three different water contents, namely, an approximately optimum water content, a lower than optimum water content, and a higher than optimum water content.

Dynamic input motion has been applied to the model embankments in a centrifugal acceleration field of 50G. Through the measurement results for the displacement, the pore water pressure, the acceleration response, and the distribution of displacement and strain provided by the image analysis with the particle tracking velocimetry (PTV) technique, the dynamic behaviors of the unsaturated embankments with different water contents have been studied.

2. Testing method and soil

2.1. Geotechnical centrifuge

In this study, the geotechnical centrifuge at the Disaster Prevention Research Institute (DPRI), Kyoto University, has been used. Fig. 1 and Table 1 show the schematic figure and the specifications of this apparatus, respectively. The effective rotation radius, defined as the length from the rotation axis of the arm to the center of the model, is 2.5 ± 0.05 m. The maximum centrifugal accelerations are 200g and 50G when using a shaking table.