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Seismic performance of small earth dams with sloping core zones and geosynthetic clay liners using full-scale shaking table tests

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Abstract

In Japan, a large number of old small earth dams are in critical need of repair due to leakage and poor earthquake resistance. In addition to cohesive soils, geosynthetic clay liners (GCLs) are used as impervious materials to repair such dams. This paper discusses the seismic performance of small earth dams, with reservoirs on their upstream side, repaired with a sloping core zone and a GCL on the basis of the results of full-scale shaking table tests performed at the E-Defense facility. The main focus is on the differences in mechanical behavior between the upstream and downstream sides of the dam. The results elucidate that the effective stress of the upstream embankment materials increased because of the undrained shear behavior of the compacted soils, although the deformation on the upstream side was larger than that on the downstream side. A large phase difference in the measured accelerations between the upstream slope and the downstream slope was also observed. Therefore, it is concluded that significant differences occurred in the dynamic behavior of the upstream side and the downstream side.

Keywords: Small earth dam; Full-scale shaking table test; Geosynthetic clay liner; Residual deformation; Excess pore water pressure

1. Introduction

There are approximately 200,000 small earth dams in Japan. Among them, around 70% were constructed more than 150 years ago and have experienced significant deterioration (Ministry of Agriculture, Forestry and Fisheries, 2017). Since these dams were constructed without modern compaction machines and techniques, their embankment stabilities are unclear. Furthermore, it is possible that a strong earthquake will occur along the Nankai Trough sometime in the next 30 years. Thus, in regions where the possibility of a strong earthquake is high, it is important to increase the earthquake resistance of the small earth dams.

In the standard method for improving small, deteriorated earth dams, a sloping core zone is built on the upstream side of the dam using cohesive soils as the impermeable materials. However, in recent years, the supply of high-quality impermeable materials at dam sites has been exhausted, and it is difficult to bring in embankment materials using dump trucks because of narrow roads. For sites where it is difficult to obtain embankment materials, small earth dams may be improved with impervious materials such as rubber membranes and synthetic resin sheets

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(Ministry of Agriculture, Forestry and Fisheries, 2015a). Geosynthetic clay liners (GCLs), which have been used at waste disposal sites, have also been adopted in recent years for the repair of small earth dams (e.g., Aoyama, 2011). However, the seismic performance of small earth dams with GCLs has not been examined, and no design guidelines for small earth dams with GCLs have been established.

With respect to earthquake damage to small earth dams, Tani and Hasegawa (1987) described the causes and modes of failure on the basis of damage survey reports on five past earthquakes, including the 1983 Japan Sea Chubu Earthquake. They reported that (1) slide failure and the lateral deformation of embankments occur approximately twice as often on the upstream side of a dam as on the downstream side; (2) the damage ratio by earthquakes is high when the foundation or embankment consists of sandy soils; and (3) serious damage, such as breaches, tends to occur when the water level is high.

With respect to earthquake damage during the past twenty years, Tani (1996) reported the features and mechanism of the damage caused by the 1995 Hyogo-ken Nanbu Earthquake. This earthquake damaged 1222 small earth dams, many of which were located within a radius of 30 km from the epicenter. The damage to some of these dams may have been caused by liquefaction. The 2011 Off-the-Pacific-Coast-of-Tohoku Earthquake damaged 750 of the 3730 small earth dams in Fukushima Prefecture via modes including slide failure and the lateral deformation of embankments (Hori et al., 2012; Mohri et al., 2014). The Fujinuma, Aotashin, and Naka Dams experienced breaches and, in particular, the breach of the Fujinuma Dam (18.5 m in height) caused severe damage to houses located downstream of the dam. According to a report put out by Fukushima Prefecture (2011), the sliding failure occurred toward the upstream side of the dam because of the decline in strength of the embankment materials, comprising highly saturated sandy soils, and due to the long period of strong ground motion. The water stored in the dam, which was full when the earthquake occurred, overflowed and breached the dam embankment.

Several researchers have examined the seismic behavior of dam embankments using physical models and numerical analyses (e.g., Hasegawa and Kikusawa, 1981; Ohne et al., 1983). Many of these studies involved the investigation of the failure process of earth dams without reservoirs. The seismic performance of earth-fill dams with reservoirs of water have also been examined by some researchers (e.g., Kim et al., 2011; Yuan et al., 2014; Kawai et al., 2015). Sendir et al. (2010) showed that the deformation of a dam body increases with decreasing relative soil density. Even though the slope was gentler at the upstream side of the dam in Sendir et al., they found that the deformation was greater on the upstream side of the dam than on the downstream side. However, the seismic behavior of embankments with sloping core zones and GCLs has only been examined in a few small-scale modeling studies (Koyama et al., 2014; Jeong et al., 2016).

To examine the seismic behavior of small earth dams that have been repaired with sloping core zones or GCLs, the authors conducted full-scale shaking table tests on two embankments as high as 3 m, as shown in Fig. 1 (Sawada et al., 2016). One embankment had a sloping core zone and the other had a GCL. When the embankments were subjected to shaking corresponding to Level-2 seismic motion, as defined in the Japanese guidelines for the seismic design of agricultural facilities (Ministry of Agriculture, Forestry and Fisheries, 2015b), large longitudinal cracks were seen to develop at the crest of the embankment containing a GCL, although no water leakage was observed in either case. Observations of embankment cross-sections by Oda et al. (2016) have revealed that the presence of a GCL can cause the development of cracks. In addition, data on the recorded accelerations around a GCL have shown that the seismic characteristics at the upstream side separated by the GCL differed from those at the downstream side. Nakazawa et al. (2017) applied three-dimensional terrestrial laser measurements to reveal the location and characteristics of cracks at the crest of an embankment with a GCL and clarified its effectiveness. However, the recorded accelerations and response pore water pressure throughout the entire embankment were not discussed in their studies and many details of the seismic behavior have not yet been clarified.

In this study, to examine the performance of small earth dams and to provide a benchmark for numerical simulations, the deformation, acceleration, and pore water pressure measured in full-scale shaking table tests are discussed. In particular, the differences in dynamic behavior between the upstream and downstream sides of the dam are addressed.

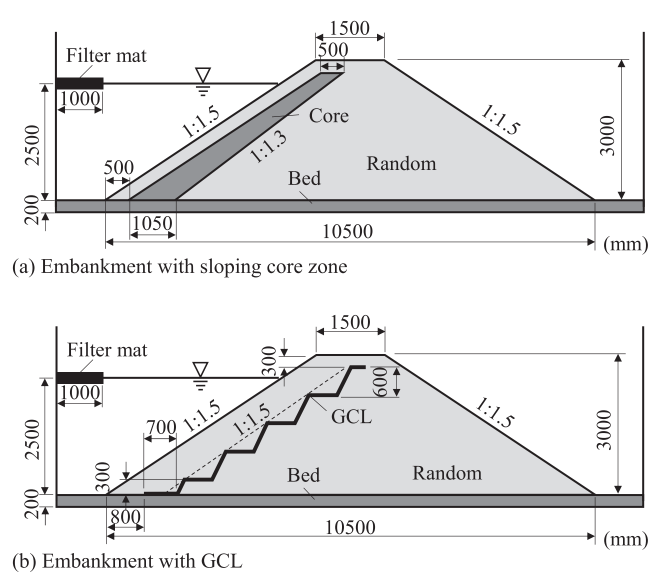

Fig. 1. Model configurations (modified from Sawada et al., 2016).

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