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Several factors affecting seismic behaviour of embankments in dynamic centrifuge model tests

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Abstract

A series of dynamic centrifuge model tests was conducted in order to evaluate some factors affecting the seismic performance of hillside embankments consisting of sandy or silty soils and resting on stiff base slope. The effects of seepage water elevation in embankments, toe drain, embankment height, base slope inclination, soil compaction, and fill materials on the seismic behaviour of embankments were investigated. The test results showed that: (1) the seepage water was one of the most important factors for earthquake-induced embankment failure; (2) the seismic performance of both the smaller and higher embankments was remarkably improved by installing the toe drain; (3) larger base slope inclination produced larger earthquake-induced deformation of embankments; (4) well-compacted embankments were not vulnerable to earthquake-induced damage; and (5) the seismic performance of well-compacted embankments consisting of well-graded silty soils with large fines content was higher than that of poorly graded sands under otherwise the same condition. In some tests, as observed during past strong earthquakes, delayed flow failure occurred due possibly to the multiple effects of upward seepage associated with the redistribution of excess pore water pressures generated during main shaking, continued small vibration after main shaking, and driving static shear stresses caused by the embankment weight. A series of triaxial compression and cyclic triaxial liquefaction tests was also conducted to evaluate undrained behaviour of the fill materials. The correlation between the model and laboratory element test results was presented.

keywords: Dynamic centrifuge model test; Seismic performance; Embankment; Earthquake; Seepage; Earthquake-induced delayed failure; Laboratory triaxial test

1. Introduction

During past strong earthquakes, embankments constructed on mountain/hill sides have frequently experienced catastrophic failures. A number of field investigations on geotechnical issues and case history studies based on these surveys have been carried out after the earthquakes (e.g., Public Works Research Institute (PWRI), 1971, 2008; Sasaki et al., 1994, 2012; Matsuo, 1996; Okimura et al., 1999; Koseki et al., 2006; Mori et al., 2012).

Among them, based on a number of reports on the field investigations conducted after the past earthquakes in Japan, Mori et al. (2012) summarized that the causes of damage to hillside embankments can be attributed to any of the followings; (1) the fill materials containing a high percentage of fine particles; (2) a shallow water table; (3) the loose state of fill materials due to poor compaction during the construction stages or due to the degradation of ground with time; and (4) poor treatment of the boundary between the fill and the original ground, leading a landslide type failure. As pointed out by Mori et al. (2012), the above-mentioned factor (1) tends to lead to poor compaction during the construction works. As an extreme example of the above-mentioned factor (2),

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based on the measurements at the road embankments damaged severely by the 2007 Noto-Hanto earthquake, it was reported that the water table existed at the surface of the embankment toe at some sites (PWRI, 2008).

Okimura et al. (1999) performed field investigations on damage to hillside embankments during the 1995 Hyogoken-Nambu earthquake. They reported that: (1) mild original slopes smaller than about 20 degrees tended to result in the accumulation of seepage water, leading to severe damage to hillside embankments; and (2) more than 15 m high hillside embankments were damaged seriously at the top of the slope due to the amplification of seismic motion caused by their heights. PWRI (2008) also indicated that hillside embankments with 15 m or more in height tended to be vulnerable to earthquake-induced severe damage and that damage tended to be severe with decreasing ratio of inclinations near the toe to behind the embankment. These results suggest that the seismic performance of embankments is also affected by their original slope inclinations and heights.

Meanwhile, to investigate the seismic behaviour of full-scale embankments and slopes, some studies using dynamic centrifuge apparatuses have been conducted (e.g., Kutter and James, 1989; Dobry et al., 1997; Pilgrim, 1998; Okamura et al., 2001; Matsuo et al., 2002; Egawa et al., 2004; Okamura and Tamamura, 2011; Higo et al., 2012). Among them, Matsuo et al. (2002) and Higo et al. (2012) showed that the seepage water in embankments was an important factor to cause earthquake-induced damage. Matsuo et al. (2002) also showed that the soil density played an important role in controlling the occurrence of earthquake-induced failure. Dobry et al. (1997), Pilgrim (1998) and Matsuo et al. (2002) reported the effects of slope inclination on the seismic behaviour of slope. Egawa et al. (2004) and Okamura and Tamamura (2011) investigated the effects of subsoil layers on the seismic behaviour by using the embankment models on peaty soft ground and soft clay deposit, respectively. However, these experimental studies have focused on the behaviour of embankments with a height of 10 m or less in prototype scale due to limited capacities of the shaking table and soil container, in spite of damage tendency related to embankment height reported by Okimura et al. (1999) and PWRI (2008). In addition, factors affecting the seismic behaviour of hillside embankments and those mechanisms have not been systematically studied.

In view of the above, in order to evaluate the effects of several factors on the seismic performance of embankments of 15 m or more in height, a series of dynamic centrifuge model tests was conducted in the present study by using a large-scale soil container. A series of triaxial compression and cyclic triaxial liquefaction tests was also conducted to evaluate the undrained behaviour of the fill materials used for the model embankment. The correlation between the model and laboratory element test results is also presented in this paper.

2. Tested materials

Fig. 1 shows the grading curves and the laboratory compaction test data of three geomaterials used for the model and laboratory element tests. The values of specific gravity (G_s), maximum diameter (D_{max}), mean diameter (D_{50}), uniformity coefficient (U_c), fines content (F_c), natural water content (w_n), optimum water content (w_{opt}), maximum dry density (ρ_{dmax}), plasticity index (I_p) and maximum and minimum void ratios (e_{max} and e_{min}) of these materials are

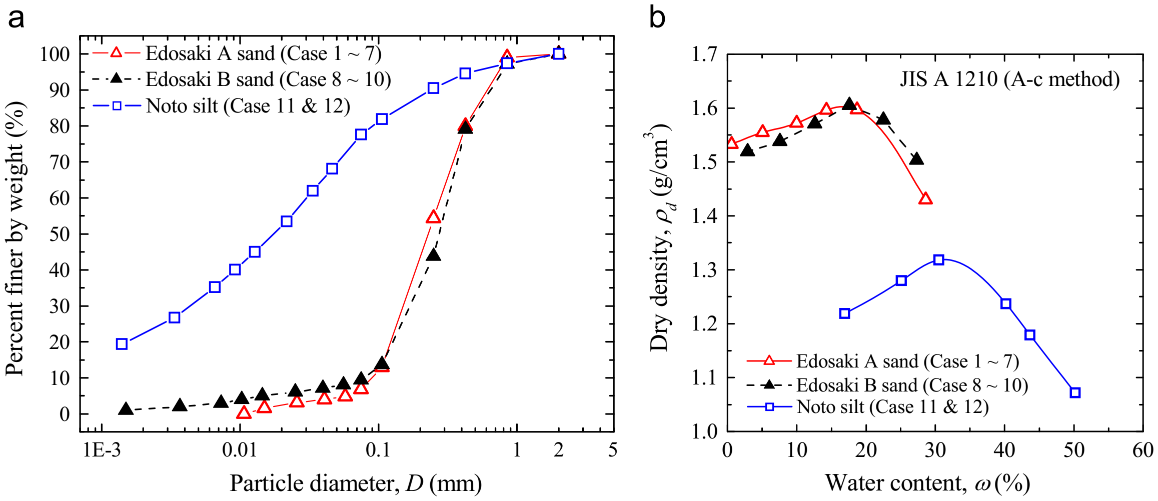

Fig. 1. Grading and compaction characteristics of geomaterials used for model and triaxial tests: (a) grading curves and (b) standard compaction test results.

Table 1
Properties of geomaterials used for model and triaxial tests.

Material	G_s	D_{max} (mm)	D_{50} (mm)	U_c	F_c (%)	ω_{opt} (%)	ω_n (%)	ρ_{dmax} (g/cm^3)	I_p (%)	e_{max}	e_{min}
Edosaki A sand	2.657	2.0	0.228	2.91	6.9	16.7	1.8	1.604	NP	1.095	0.609
Edosaki B sand	2.732	2.0	0.278	3.91	9.4	18.1	7.4	1.605	NP	-	-
Noto silt	2.696	2.0	0.0177	-[a]	77.6	31.1	39.5	1.318	29.8	-	-

[a] The value of D_{10} was not obtained.