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Interpretation of the mechanical behavior of embankments having various compaction properties based on the soil skeleton structure

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Abstract

After the Hanshin Awaji Earthquake disaster, the seismic resistance of embankments was evaluated, and design principles were changed from specification-based to performance-based. However, compaction properties and the mechanical behavior of compacted soil were not sufficiently considered in the Manual of Highway Earthworks on Embankments.

The first objective of the present study is to reproduce the mechanical behavior of three embankment materials having different compaction properties. A series of triaxial compression tests and oedometer tests is carried out. The mechanical behavior is reproduced by the SYS Cam-clay model and the influence of compaction on the mechanical behavior is interpreted based on the soil skeleton structure. The second objective is to evaluate the seismic stability of the embankment, which depends on the compaction properties of the embankment material, using GEOASIA, a soil–water coupled finite deformation analysis code.

The primary conclusions are as follows. (1) Through the triaxial tests, the maximum deviator stress increases as the degree of compaction, Dc, increases. However, the trends in the increase differ depending on the material. (2) Based on one-dimensional consolidation tests, the compression curve is approximately a straight line with a large vertical effective stress. In the present study, a greater maximum dry density corresponds to less compressibility and a lower compression curve. (3) The mechanical behavior of each material is reproduced by the SYS Cam-clay model using one set of material constants for each material and representing the differences in Dc by different initial conditions for the structure and overconsolidation. An increase in Dc causes the decay of the structure, as well as the accumulation of overconsolidation. In the case of material A, the decay of the structure and the loss of overconsolidation occur quickly, whereas in the case of material C, the decay of the structure is slight and the loss of overconsolidation is moderate. (4) The seismic response analysis reveals different deformations of the embankment for different materials, even for the same Dc. The seismic stability of the embankments was increased by increasing Dc. Materials, such as material A, that have fast decay of the structure and fast loss of overconsolidation produce embankments with high seismic stability.

Keywords: Compaction; Embankment; FEM analysis; Soil–water coupled analysis; Soil skeleton structure; Triaxial test

1. Introduction

Embankment stability has progressed dramatically since the fundamental principle of soil compaction was proposed by Proctor (1933). In Japan, a number of studies on compaction

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have been conducted and a number of problems have been solved, particularly during the construction of dams and expressways (Mikuni, 1963; Kuno, 1974; Shima and Imagawa, 1980). In addition, progress has been made in many studies on the behavior of compacted soils in the world (Escario and Sáez, 1986; Wheeler and Sivakumar, 1995, 2000; Maâtouk et al., 1995; Kong and Tan, 2000; Toll and Ong, 2003; Cokca et al., 2004; Heitor et al., 2013). Most of these researches concentrated on the strength properties, i.e., cohesion and the friction angle and so on, of unsaturated compacted soils rather than the mechanical behavior of compacted soils. In current research, some researchers suggest constitutive models for unsaturated soil and try to express the mechanical behavior of compacted soil with density and the initial condition by using their model (Alonso, et al., 2013; Zhou and Sheng, 2014).

After the Hanshin Awaji Earthquake disaster in Japan, the road earthwork guidelines for the construction of embankments were revised in order to evaluate the seismic resistance of embankments, and the design principles were changed from specification-based to performance-based (Japan Road Association, 2010). However, even under these new guidelines, the properties of compaction and the mechanical behavior after compaction, which depend on the geomaterial, were not taken into consideration. Recently, road embankments in Japan have often failed due to earthquakes, such as the Mid-Niigata Prefecture Earthquake of 2004, the Noto Hanto Earthquake of 2007, the earthquake in Suruga-wan in 2009, the Great East Japan Earthquake of 2011 and so on. Therefore, it has become increasingly important to evaluate the seismic resistance of embankments. In most cases of the failure of embankments, the rainfall before the earthquake caused more severe damage and a larger disaster. This implies that the higher the degree of saturation of the embankment, the more danger there is to the embankment. Nakamura et al. (2012) reported that the degree of saturation of the geomaterials in four embankments along expressways rose to more than 90%. Generally, embankments are evaluated at their unsaturated states. In most of the above-mentioned studies, the compacted soils were regarded as unsaturated soils, and the compaction behavior should be described by the theory of unsaturated soil. However, in this study, saturated embankments were treated taking into consideration their high risk conditions.

The objective of this study is to evaluate the deformation behavior and stability of three embankments due to an earthquake. Three types of geomaterials with different grain size distributions and different compaction properties were selected, and the saturated compacted soil specimens were subjected to triaxial compression and odometer tests, with the objective of obtaining basic data in an attempt to reproduce the mechanical behavior of various materials after compaction. The shear behavior and one-dimensional compression behavior after compaction were compared and examined in accordance with the differences in the materials. In addition, the effect of compaction on the mechanical behavior of the embankment materials was interpreted based on the soil skeleton structure concept by reproducing the mechanical behavior using the super/subloading yield surface Cam-clay model (referred to hereinafter as the SYS Cam-clay model) (Asaoka et al., 1998, 2000, 2002). Moreover, seismic deformation and stability analysis of the three embankments were carried out using the soil-water coupled finite deformation analysis code GEOASIA (Noda et al., 2008), which incorporates the SYS Cam-clay model into it.

2. Physical and compaction properties of three types of embankment materials

Three types of embankment materials were examined in the present study. The materials are referred to as materials A, B, and C. Table 1 shows the physical properties of the materials, while Fig. 1 shows the grain size distributions at each site. Material A contains more than 70% coarse fraction, whereas materials B and C contain more than 50% fine fraction. The coarsest material is A, followed by B and C.

Fig. 2 shows the results of compaction tests conducted on the three types of materials. The compaction tests were

Table 1
Physical properties.

	Material A	Material B	Material C
Soil particle density (g/cm^3)	2.67	2.67	2.73
Liquid limit (%)	36.4	42.7	60.5
Plastic limit (%)	20.9	19.6	42.3
Plasticity index (%)	15.5	23.1	18.1

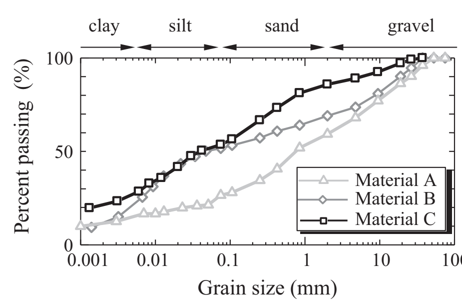

Fig. 1. Grain size distribution.

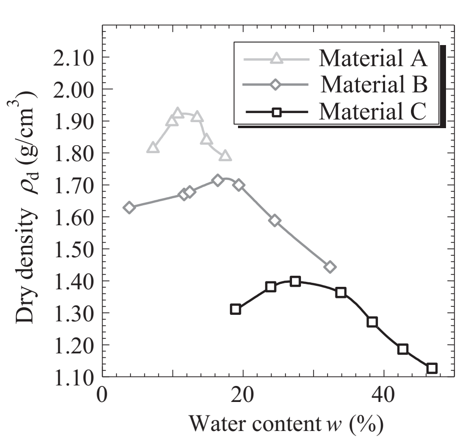

Fig. 2. Compaction curves.