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Liquefaction-induced deformation of earthen embankments on non-homogeneous soil deposits under sequential ground motions

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ABSTRACT

Damage of embankments during earthquakes is widely attributed to the liquefaction of foundation soil. Previous studies have investigated the dynamic response of embankments by mainly considering uniform sand foundation and a single earthquake event. However, the foundation of an embankment consists of many sublayers of soil from liquefiable sand to relatively impermeable layer, and during earthquakes a mainshock may trigger numerous aftershocks within a short time which may have the potential to cause additional damage to soil structures. Accordingly, the investigation of liquefaction-induced deformation of earthen embankments on various liquefiable foundation conditions under mainshock–aftershock sequential ground motions is carried out by a series of dynamic centrifuge tests in this study. The liquefiable foundation includes uniform sand profile, continuous layered soil profile, and non-homogeneous soil profiles. Effects of various foundation conditions on embankment deformations are compared and analyzed. From the test results, it is found that the embankment resting on non-homogeneous soil deposits suffer more damage compared to the uniform sand foundation of same relative density. The test results also suggest that the sequential ground motions have a significant effect on the accumulated deformation of embankment.

1. Introduction

Earthquake induced liquefaction has become a major problem to soil embankments such as river dykes, levees, road embankments and earth dams, supported on a cohesionless foundation soil. Previous studies have shown that the widespread damage to such embankments occurred mainly due to the liquefaction of foundation soil, resulting in cracking, settlement, slumping and lateral spreading [1–5].

Several experimental studies and numerical analyses have been conducted previously to examine the behavior of embankments resting on uniform clean cohesionless soil during earthquakes [2,4,6,7]. Previous studies that proposed various techniques for mitigation of liquefaction-induced damage in uniform ground have also been reported [4,7]. It is noted however, that natural sand deposit normally consists of many sublayers with different soil particles and properties, ranging from soft sand lenses to stiff cohesive clay and coarse sand layers, referred to as non-homogeneous soil deposits (Fig. 1). Kokusho [8,9] has studied the formation of water film beneath the thin impermeable silt due to difference in permeability in layered sand and its role in the extent of lateral deformation in the sloping surface. Malvick and coworkers [10,11] conducted centrifuge tests to demonstrate the shear localization due to void redistribution and its consequences on large postshaking deformations in a sand slope with continuous embedded silt layers. In a previous study [12,13] we conducted centrifuge model tests and numerical analyses to investigate the liquefaction mechanism in non-homogeneous soil deposits. Non-homogeneous soil deposits were modeled based on the features of actual soil profile with discontinuous low permeability layers in multi-layered sand deposits. Non-homogeneity in foundation was incorporated by including periodically distributed silty sand patches of a lower permeability than the liquefiable sand. It was found that excess pore water pressure remains for a longer period of time at discontinuous regions in non-homogeneous soil deposits compared with the continuous layered and uniform soil deposits, manifesting a larger settlement at that corresponding region causing non-uniform settlements. Nonetheless, most of the embankments rest on non-homogeneous liquefiable soil profiles, which consist of thin layers of discontinuous low permeability layers like silty sand or clay. Oka et al.[14] performed numerical modeling of river embankments on a foundation with various soil profiles and ground water tables, including a clayey soil layer. However, most previous studies have only investigated

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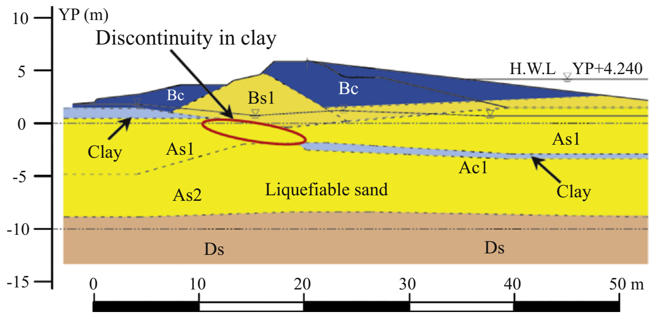

Fig. 1. Non-homogeneous soil profile along levee in Tone River (Left levee at 32.3 km) (courtesy of Kanto Regional Development Bureau of Ministry of Land, Infrastructure, Transport and Tourism, Japan).

the dynamic behavior of embankments resting on uniform sand. Thus, the dynamic behavior of earthen embankments on a liquefiable non-homogeneous foundation, consisting of discontinuous low permeability layers of silt or clay at different depths is not well understood. Despite the extensive research and development of remedial measures to prevent the large deformation of soil structures, embankments have suffered severe damage during past earthquakes. During 2011 Great East Japan Earthquake, Japan's Ministry of Land, Infrastructure, Transport and Tourism (MLIT) documented that more than two thousand locations of levee suffered some level of damage [14,15]. The minor to major damage was attributed due to the liquefaction of foundation soil. This event elucidates the further need to understand the deformation behavior of embankment resting on non-homogeneous liquefiable foundations.

Repeated ground-motion sequences occurring after short intervals of time, resulting from mainshock–aftershock earthquakes, have been observed during many earthquakes [16]. Previous studies have pointed out that the low-amplitude aftershock can accumulate large lateral deformation and continue for several minutes on the liquefied soil [17–19]. Ye et al.[20] conducted shaking table tests and numerical analyses on saturated sandy soil to investigate the mechanical behavior of liquefiable foundations during repeated shaking and consolidation. Xia et al.[21] presented numerical analysis of an earth embankment on liquefiable foundation soils under repeated shake-consolidation process. However, in most of the previous experimental and numerical studies seismic performance of soil structures is investigated by applying only a single earthquake, ignoring the influence of repeated earthquake phenomena. During 2011 Great East Japan Earthquake, the liquefaction-vulnerable structures continued to shake after the onset of soil liquefaction for more than two minutes. Moreover, during the reconnaissance survey after 2011 Great East Japan Earthquake, Sasaki and his team [22] found that the more severe deformation and subsidence of levees was due to the occurrence of aftershock, 30 min after the mainshock. Moreover, no previous study has examined the effects of repeated earthquakes on embankments lying on non-homogeneous soil deposits. Therefore, to understand the deformation mechanism of embankments lying on non-homogeneous soil deposits under mainshock and sequential ground motion is of great importance.

This paper presents the results of dynamic centrifuge tests conducted on different foundation conditions: one involving a uniform foundation; one involving a continuous silty sand layer foundation; and three involving non-homogeneous discontinuous silty sand layer foundations. The work presented herein compares the liquefaction-induced deformation of embankments resting on different foundations under mainshock and sequential ground motion.

2. Centrifuge testing program

Five dynamic centrifuge tests were conducted on three different liquefiable foundations utilizing the Tokyo Tech Mark III centrifuge of radius 2.45 m, at a centrifugal acceleration of 40 g. The model configurations and the entire test results are presented and discussed in prototype scale units, unless indicated otherwise. All tests simulated a prototype soil deposit of 8.4 m depth and embankment of 1.2 m height. Toyoura sand and Silica sand No. 8 was used in the tests to model the foundation (Table 1). It is noted that Toyoura sand, also referred to as fine sand, was deposited at a relative density $D_r \approx 50\%$. Silica sand No. 8, also referred to as silty sand, was deposited at a relative density $D_r \approx 50$–55%, and used to create the relatively impermeable layer in layered soil profiles. DL clay, which consists of 90% silt and 10% clay, was mixed with 22% silicon oil by weight to build the embankments, with 1:2 slopes having a unit weight of 16 kN/m^3. The model configurations are shown in Fig. 2 and Table 2: Model NHG1 and Model NHG2 simulate non-homogeneous foundations consisting of fine sand layers with two discontinuous silty sand layers of thickness 1.0 m (Fig. 2(a) and (b)); Model UG simulates homogeneous uniform sand foundation consisting of only Toyoura sand (Fig. 2(c)); Model CG simulates non-homogeneous soil deposit with continuous silty sand layers (Fig. 2(d)). An additional test, Model NHG1-MS was also conducted, which consists of the same non-homogeneous foundation as Model NHG1, but only having a mainshock applied.

A flexible laminar container with inner dimensions of $500 \times 200 \times 450$ mm in length, width, and height, respectively was used to build the models. The box is composed of 20 aluminum alloy rectangular rings which allow the container to move with the soil, creating a flexible boundary and ensuring the uniform distribution of dynamic shear stresses within the soil. The foundation was prepared by air pluviation to a depth of 210 mm in model scale. The sand was poured from a hopper which was manually moved back and forth along the longest dimension of the box, while the falling height was kept constant to obtain the desired relative density. During the preparation of non-homogeneous soil deposits, Toyoura sand was deposited first and then, the remaining parts were filled with Silica sand No. 8 (Fig. 2(c) and (d)). Trapezoidal silty sand patches were chosen to model the multi-layered soil profile consisting of discontinuous thin layers of low permeability observed in many damaged sites during past earthquakes [23,24]. After the foundation was constructed, the embankment was built of a mixture of DL clay and silicon oil with 1:2 slopes. The models were saturated with a viscous fluid, i.e., a mixture of water and 2% Metolose (Hydroxypropylmethyl cellulose from Shin-Etsu Chemical Company) by weight of water, to achieve a viscosity of about 40 times the viscosity of water. The density and surface tension of this solution is practically identical to that of water [17]. Also, the viscous fluid simulates the actual prototype permeability of the soil. The de-aired Metolose solution was dripped slowly from the top of the container under a vacuum of 760 mmHg which slowly moves downwards. In this process, the water table rises from the bottom. The saturation was continued until the solution level reached the elevation of 210 mm in model scale, i.e., the water table is at the free field surface. The saturation

Table 1
Index properties of soils.

Property	Toyoura sand	Silica sandNo. 8
Specific gravity, G_s	2.65	2.65
D_{50} (mm)	0.19	0.10
D_{10} (mm)	0.14	0.041
Maximum void ratio, e_{max}	0.973	1.333
Minimum void ratio, e_{min}	0.609	0.703
Permeability, k (m/s) at $Dr=50\%$	2×10^{-4}	2×10^{-5}
Sand %	100%	75%
Silt%		25%