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Analysis of the effect of groundwater level on the seismic behavior of an unsaturated embankment on clayey ground

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ABSTRACT

Numerous river levees on clayey soil grounds were damaged by the 2011 off the Pacific coast of Tohoku Earthquake. In order to investigate such damage, the behavior of an unsaturated embankment on clayey ground was simulated during its construction, during an earthquake and after the earthquake. The simulation was carried out using a soil–water–air coupled finite deformation analysis code, with attention being focused on the effect of groundwater level. The results indicated that if the groundwater level is high, a saturated area (settlement-induced saturation area) is formed at the base of the embankment due to penetrative settlement during/after construction. In addition, the mean skeleton stress is low compared with the low groundwater level. As a consequence, in the embankment on ground with the high groundwater level, the co-seismic deformation is greater and the mean skeleton stress decreases sharply, particularly in the settlement-induced saturation area during the earthquake. It was also shown that after the earthquake, the groundwater level rises because water flows toward the unsaturated embankment from the settlement-induced saturation area and/or the saturated clayey ground. If the groundwater level is high, in particular, a phreatic line is formed temporarily within the embankment.

1. Introduction

The off the Pacific coast of Tohoku Earthquake of 11 March 2011 caused massive damage to grounds and earth structures. Damage to river levees was especially prominent and has received much attention. Although liquefaction of sandy foundation grounds has been the focus of attention in investigations of seismic damage to river levees, the earthquake caused collapse of river levees on clayey foundation grounds in several areas. A number of studies [1–3] have suggested that collapse occurs through the following mechanism: deformation of clayey ground during construction of a levee embankment causes settlement of the base of the embankment to below the groundwater level, and this leads to formation of a saturated area at the embankment's base. The saturated area is termed "settlement-induced saturation area" hereafter. The presence of this settlement-induced saturation area, in combination with decreases in the horizontal stress and density of the embankment's base, produces liquefaction of the settlement-induced saturation area during the earthquake and the consequent collapse of the levee embankment. Damage caused by liquefaction of an settlement-induced saturation area had already been pointed out with respect to the collapse of a river levee on peat ground during the 1993 Kushiro-oki Earthquake [4] but came to receive wide attention after the extensive damage caused by the off the Pacific coast of Tohoku Earthquake. Analytical and experimental research have been carried out with the aim of clarifying the mechanism of such damage. In an analytical study, Uzuoka and Semba [5] carried out a soil–water–air coupled finite deformation analysis and compared, before seismic response analysis, the result in which the deformation process during embankment construction is taken into account with the result in which the deformation process is not taken into account. The comparison showed that in the former case, the deformation produced during embankment construction decreases the mean effective stress at the base of the embankment, which results in the deformation produced during and after an earthquake becoming large. The experimental work of Okamura et al. [6] using centrifuge tests to simulate the behavior of an embankment during construction and earthquake showed that a saturated zone is formed at the base of the embankment due to deformation of the foundation

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ground during construction and that collapse of the embankment is related to the existence of this saturated zone and to the decreases in effective stress and density at the embankment base. A Technical Committee for Study of Restoration Techniques of Levees along the *Kitakamigawa* River and Other Rivers [3] was set up by the Tohoku Regional Development Bureau, Ministry of Land, Infrastructure, Transport and Tourism, to survey and interpret the actual extent of damage to levees caused by the off the Pacific coast of Tohoku Earthquake and propose suitable restoration measures. The committee's report describes the actual conditions and features of the damage, focusing on the microtopography, soil characteristics and groundwater levels. Regarding groundwater levels, the committee's report offers the following statements.

> "It has been observed that in the *Edano* and *Shimonakanome* upstream regions, groundwater is present in the bottom parts of the damaged levee cross sections, whereas groundwater is not present in the bottom parts of the undamaged levee cross sections."
>
> "It has been observed that at 16 locations except the *Sunayama*, *Wadatanuma*, *Kimatsuka*, *Hashiura* and *Nakano* regions, the levels of groundwater present within the levees are equal to or higher than the inland ground heights (or high water bed heights). In contrast, groundwater was not present in the undamaged levee cross sections or the ground water levels were lower than those in the damaged levee cross sections."

Fig. 1 shows the cross section of the *Narusegawa* river levee in the disaster-affected *Shimonakanome* region, 30.0 km upstream of the river mouth. This figure is a partly redrawn version of the one in Sasaki et al. [1]. What is meant by "groundwater is present in the bottom part of the damaged levees" in the abovementioned report is that the groundwater surface was observed to be convex upward within the levee, as can be seen in Fig. 1. It is believed that this groundwater surface was already present before the earthquake. Although research is being carried out to improve the accuracy of simulation of seepage lines that are convex upward, such simulation is considered to be difficult if actual rainfall is used in the seepage analysis [7].

With the above background in mind, this paper utilizes the soil-water-air coupled finite deformation analysis code [8] to numerically simulate the behavior of an unsaturated embankment on clayey foundation ground, focusing attention on the difference in groundwater levels. The behavior during embankment construction, during an earthquake and after the earthquake is simulated as an approach to clarify the mechanism of the damage described above. This analysis code is based on the soil-water coupled finite deformation analysis code [9], which is mounted with the SYS Cam-clay model [10] that allows description of soils ranging from sand through to clay, including even intermediate soils, within the same theoretical framework and is capable of determining deformation and collapse phenomena without distinguishing between dynamic and static behavior. The above code was extended to make it applicable to unsaturated soils as well, and it is capable of handling saturated and unsaturated conditions seamlessly. The two specific cases analyzed were (1) a ground with the groundwater level set to coincide with the ground surface initially (high initial groundwater level) and (2) a ground with the groundwater level set to be 2 m below the ground surface initially (low initial groundwater level). Unsaturated embankments were constructed on the two types of ground, and the calculations were continued until consolidation had ended (i.e., until the excess pore water pressure had completely dissipated), after which seismic response analysis was carried out in order to clarify how the difference in groundwater level affects the mechanical behavior. The existence of a seepage line within the levee before the earthquake was not assumed when setting the initial groundwater level in the current study, unlike in a previous study [7]. This paper shows that when the initial groundwater level is high, a seepage line is formed temporarily within the unsaturated embankment after the earthquake and discusses the mechanism of this phenomenon.

2. Analytical conditions

Fig. 2 is an outline of the cross section analyzed, showing mainly the hydraulic boundary conditions and the air boundary conditions. Assuming two-dimensional plane strain conditions, the cross section was configured by reference to Fig. 1, however, study of alternately layered grounds of clayey and sandy soils or detailed investigations of damaged cross sections of former levees in the *Shimonakanome* region, etc. are not carried out here. The objective of this work was to carry out three-phase finite deformation analysis of unsaturated embankments on clayey grounds under simple conditions and discuss the results thus obtained. The width set for the cross section analyzed is greater than 500 m. Note that the surroundings of the embankment are shown magnified in Fig. 2. Distribution diagrams of strain, stress and other quantities obtained through the analysis are shown in the following sections and in these diagrams, too, the surroundings of the embankment are shown magnified. The hydraulic boundary condition assumed for the ground and embankment surface was that of constant total head (potential head + pressure head), and the air condition was the exhausted condition, i.e., always at atmospheric pressure. All other boundaries were in the undrained and unexhausted condition. Hydraulic boundary conditions of actual ground/embankment surfaces are complicated because rainfall and evaporation repeatedly occur. In this analysis, for simplicity, assuming that a groundwater level becomes constant in a steady state, the constant head hydraulic boundary condition was set. The reference plane for the potential water head was set at the lower end of the analyzed section (engineering bedrock). The analysis was performed for 2 cases. The first case was for the initial groundwater level being coincident with the initial ground surface. This case will be referred to as GL-0m hereafter. The second case was for the initial groundwater level being located 2 m below the initial ground surface, hereafter referred to as GL-2m.

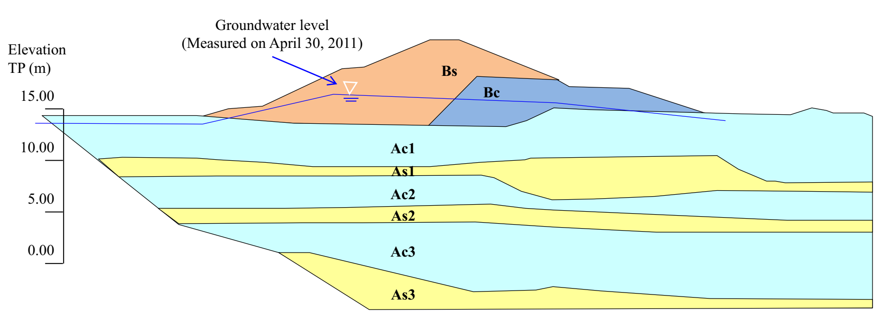

Fig. 1. Cross section of the *Narusegawa* river levee in the disaster-affected *Shimonakanome* region, 30.0 km upstream of the river mouth. (This figure is a partly redrawn version of the one in Sasaki et al., 2012).