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The uplift behavior of a subway station during different degree of soil liquefaction

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Abstract

The large underground structures, such as the subway station, deposited in the saturated liquefiable soils are easily subjected to severe damages due to the liquefaction-induced uplift in the strong earthquake. Existing researches of the liquefaction-induced uplift primarily focused on the seismic response of underground structures after soil liquefaction. However, relatively little effort has been dedicated to discussing the uplift behavior in the beginning of soil liquefaction during earthquakes and after soil post-liquefaction when the earthquake stopped. A subway station deposited at different buried depths within different relative density sands suffered from a moderate earthquake was simulated by a Finite Element and Finite Difference (FE-FD) Coupled Method to detect the issue in this study. It was found that soil liquefaction induced by the earthquake loading was a precondition of the uplift trigger, but not a basic reason, both sinking and floatation failure could take place during soil liquefaction. The degree and the area of soil liquefaction surrounding the underground structure and the surrounding soil squeezing into the bottom of the flowing underground structure after seismic liquefaction were the fundamental conditions. The results also showed that when the uplift response occurred, the uplift displacement slowly developed between the elementary liquefaction and the complete liquefaction, and then rapidly developed after the complete liquefaction, but did not cease immediately when the earthquake stopped, whereas still slowly developed, and then settled in some extent with the dissipation of excess pore water pressure.

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Keywords: Earthquakes; Uplift behavior; Degree of liquefaction; Numerical analysis; Subway station

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1. Introduction

The uplift of underground structures is one of damage phenomena of liquefaction-induced disasters, which has been investigated and found after several strong historical earthquakes. Based on the earthquake events, it can be concluded that underground structures, e.g. sewer pipes, manholes, tanks, tunnels, and subway stations, suffered from major uplift damages were caused by soil liquefaction and subsequently losing of its shear resistance against the uplift force from the buoyancy of underground structures, and the necessary conditions of the development of this failure phenomenon were high excess water pressure and large input acceleration [1,2]. In the last few decades, in order to understand the complex uplift behavior of underground structures subjected to seismic liquefaction, numerous researchers focused on it by model tests including shaking table test and centrifuge test [3-6] and numerical modeling measures [2,7-11]. These efforts found that the structures suffered from severe damages due to floatation after soil liquefaction and discussed the influence of some factors on the uplift deformation, in which both Chain et al. [2] and Kang et al. [12] found that the structures commenced floatation when excess pore water pressure reached approximately 100% of the initial effective vertical stress and high excess pore pressure, and then ceased as soon as the earthquake shaking stopped, whereas Liu and Song [8] analysed post-earthquake response of underground structures in saturated liquefiable soils and found that the development of the uplift behavior of the underground structure did not cease immediately after the earthquake stopped, instead of continuing till up to some extent dissipation of the excess pore pressure, and the underground structure started to settle afterwards, but with a magnitude much smaller than the amount of the uplift displacement. Thus, the findings of these researchers were contradictory to each other that needed to be clarified and investigated in detail. The uplift behavior of underground structures during different states of soil liquefaction and during the dissipation of excess pore water pressure after earthquake loadings have not been studied in detail. Therefore, it still needs to in-depth conduct the research to better understand and mitigate the uplift behavior during seismic liquefaction, particularly in the presence of the elementary liquefaction and during the post-earthquake-time.

Several researchers revealed that the magnitude of the uplift was significantly influenced by the different burial depths of the underground structures and the different relative densities of liquefiable soils [1,4,10,13]. In this study, therefore, a Finite Element and Finite Difference (FE-FD) Coupled Method was used to stimulate the uplift response of a two-story subway station deposited at different depths in the saturated sands with different relative densities during a moderate earthquake, in order to identify the trigger conditions of the uplift of the subway station, also the degree and the area of soil liquefaction and the displacement of the underground structure were investigated, which can provide a direct guidance for the earthquake design procedures.

2. Numerical analysis method and Finite element model

The constitutive model and a finite element model used in this paper were described briefly in this section. A novel FD-FE method was firstly proposed by Akai and Tamura [14] for respective discretization of the equilibrium equation of the water-soil by Finite Element Method (FEM) and terms of pore water pressure of the continuity equation by Finite Difference Method (FDM). Subsequently, a cyclic elastoplastic constitutive model was presented by Oka [15] based on the FD-FE method. The differences of the constitutive model from other elastoplastic constitutive models were that the non-associated flow rule and the improved nonlinear kinematic hardening rule were adopted to revise the characteristic curve of stress-strain. In addition, some special parameters of soils, such as dilatancy parameters and hardening parameters, were used for better describing the characteristic of the stress path and the process of soil liquefaction. A soil-water coupled problem was formulated based on the u-p (displacement of the solid phase-pore water pressure) formulation [16]. In spatial domain, the FD-FE method was conducted to reduce the degree of freedom of the equilibrium equation and the continuity equation and to obtain the governing equation with u and p format, which can effectively avoid the problem induced by inconformity of the interpolation functions of u and p, and then the Newmark implicit method was used for discretization of the governing equation in time domain. The numerical method in this paper has been validated by comparison of the results of a series of centrifuge tests and the actual damages of a dam in the 1933 Hokkaido Nansei-Oki Earthquake [17], simulating the seismic response of a pile group on the liquefied ground [18], and the uplift behavior of a large underground structure in the liquefied field [11,19].

The uplift behavior of a subway station subjected to seismic liquefaction was investigated in this paper. The