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Numerical analysis on the seismic behavior of a large metro subway tunnel in liquefiable ground

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ABSTRACT

This paper aims to investigate the seismic behavior of a large rectangular metro tunnel in liquefiable soil deposit. The study is performed by an effective stress based soil-water fully coupling finite element-finite difference (FE-FD) method with consideration of the excavation process during structure construction. The behavior of the foundation soils are described by a cyclic elasto-plastic constitutive model in which, the stress-induced anisotropy, the density and structure of ground can be described in a unified way, while the tunnel structure is simulated using elastic solid elements and beam elements. A static calculation is first carried out in three steps to reflect the construction process of the tunnel structure, and after the initial stress field of the ground due to the gravitation is establish, the calculation is automatically changed to dynamic analysis with the input earthquake motion. The results show a matching uplift response of the structure, acceleration, pore water pressure and ground displacement in liquefied soil deposits. The seismic behavior and floatation mechanism of the large metro tunnel structure in liquefied soil deposits has been clarified sufficiently. The displacement of soil around the rectangular structure was confirmed to resemble a flow mechanism from two sides of the structure to its invert which is different from the global circular flow mechanism of circular tunnels. The influence of vertical input motion is also simulated. Last, the effect of a mitigation method with different reinforcement thicknesses to reduce the uplift of the structure is discussed. The results show that the injection grouting method to reduce the uplift of structure is of important meaning in engineering practice.

1. Introduction

With the increase in demand on land in urban areas, shallowly buried underground structures are widely constructed. Although observations show that underground structures perform better than surface structures when subjected to the same seismic excitation, these underground structures are susceptible to damage during a major earthquake, especially those which are constructed underground in a liquefiable layer (Arango, 2008). Metro tunnels, large underground car parks, pipelines and manholes suffered significant uplift in liquefied soil as observed in numerous earthquake events (Hall and O'Rourke, 1991; Wang et al., 2001; Liu and Song, 2005; Tokimatsu et al., 2012). Fig. 1 shows an example of floatation of water tubes due to liquefaction in the 2011 Great East Japan Earthquake. It is clear in Fig. 1 that water tubes had floated to the surface and scattered widely when the surrounding ground had experienced severe liquefaction, and some of them were 100 meters away from the original site. Further analyses on the performance of underground pipes confirmed that the phenomenon of significant uplift displacement in liquefiable soil deposits is in agreement with the damage of these pipes observed in the 2011 Great East Japan Earthquake (Chian and Tokimatsu, 2012).

The underground structures are generally subjected to a buoyant force due to their lower submerged unit weight compared to the surrounding soils. Seismic behavior of tunnels and other underground structures can be studied using numerical analysis or physical tests. Numerical analyses on tunnels in specific cases and site conditions can be found in the literatures (Adalier et al., 2003; Sun et al., 2008; Azadi and Mir Mohammad Hosseini, 2010a, 2010b). Centrifuge tests (Chou et al., 2011; Tobita et al., 2011) were carried out to substantiate the basic failure mechanisms that, the uplift could be affected by both the input earthquake shaking intensity and the generation of excess pore pressure. Ling et al. (2003, 2008) conducted centrifuge model test and numerical analysis to simulate the dynamic response of soil and pipe up to the stage of initial liquefaction. Chen et al. (2013) conducted a series of shaking table tests to investigate the seismic failure characteristics of a three-story and three-span subway station structure on the liquefiable

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Fig. 1. Ground damage and floatation of U-shaped water tubes due to liquefaction in the 2011 Great East Japan Earthquake (Chian and Tokimatsu, 2012).

ground. Some studies (Yang and Wang, 2013; Unutmaz, 2014; Madabhushi and Madabhushi, 2015) indicate that the response of the tunnel structure depends on tunnel depth, soil stiffness, water table elevation and properties of seismic loading (frequency, excitation duration, peak acceleration etc.). It was postulated that the primary cause of uplift is the reduction of the effective confining stress near the bottom of structures due to strong shaking (Sasaki et al., 1999). Koseki et al. (1997) studied the factor of safety against floatation of underground structures in liquefiable soil. However, large soil strain simulation during post-liquefaction process remains a challenge to date with conventional numerical methods. Most of these studies focus on the damages happen to small underground structures. Existing reports about damages to large underground structures are still limited. Liu and Yuan (2015) pointed out that the cross-sections of transit tunnels are usually larger than those of pipelines used to carry oil and gas and the results of the pipeline research can serve as references for the uplift mechanism using the similarity theory when investigating the mechanical behavior of transit tunnels. However, the condition for the transit tunnels might be more complex because of the large cross-sections and shallow earth cover that may not ensure the anti-buoyancy safety of the large cross section tunnels. Moreover, the rapid and extensive development of cities and their underground structures (Azadi and Mir Mohammad Hosseini, 2010a), such as large metro subway tunnels, pipe line tunnels etc. (particularly in areas of high seismicity and liquefaction potentials), make it quite necessary to evaluate the mechanical behavior and safety of these structures (Chen et al., 2014). Thus, the influence of ground liquefaction when constructed in liquefiable soil deposits becomes more extensively (Huang et al., 2015).

Additionally, the dynamic behavior of underground structures in liquefiable soil deposits mainly depends on the nonlinear material properties of liquefied or partly liquefied soils. Much of the research on the floatation of tunnels or pipelines outlined above falls in one important category that the seismic behavior of soils was not described accurately by constitutive models. As confirmed in the work by Tian and Cassidy (2008), using a proper constitutive model to accurately describe the soil behaviors becomes a key factor when assessing the behavior of underground structures and solving the soil-structure interaction problems. Therefore, it cannot infer general findings from a limited number of experiments. Further study of dynamic tunnel structure behavior in liquefied ground through simulations of model tests or case histories, along with effective stress based soil–water coupled analysis is required. Moreover, the construction stages should also be taken into account which may provide a more severe condition for liquefaction during an earthquake. Because unloading of the soil due to excavation could influence the uplift behavior of the structure, the excavation process during structure construction should be considered in an analysis of tunnel uplift mechanism.

Thus, in this paper, the main focus is on the seismic performance of a large metro subway tunnel structure located in liquefiable soil deposits with consideration of the excavation process during the structure construction. The input earthquake motion is taken from 1995 Kobe earthquake. The soils are simulated with a kinematic hardening elasto-plastic cyclic mobility model. The element behavior of ground soils is simulated first to validate the constitutive model and soil parameters. Then the seismic behavior of the tunnel structure including the influence of vertical input motion is investigated using the soil-water fully coupling finite element-finite difference (FE-FD) code DBLEVES (Ye, 2011). Last, the effect of a mitigation method with different reinforcement patterns to reduce the uplift of the structure is discussed. Particular attention is devoted to the changes of excess pore water pressures, stress path, response acceleration, deformations and state parameters during the earthquake motion.

2. Case study

The analysis was carried out under plane strain assumptions and a large rectangular cut-cover metro tunnel was selected as the computational model. Fig. 2 shows the computational model and soil profiles. The dimension of the domain is taken as 250 m in length and 50 m in depth. The tunnel structure had the dimension of 22 m × 12.5 m to represent a metro tunnel that can accommodate two-story railway lines. The embedment depth of the tunnel was 3 m below ground surface. The soil deposits are supposed to be homogeneous loose Toyoura sand with relative density Dr = 50% and clayey soil lying underneath. The thickness of sand layer was assumed to be 30 m, while the underlying clay was 20 m in thickness. The FE mesh and boundary conditions are shown in Fig. 3. The mechanism of the liquefaction related seismic behavior of underground structures could be extensively examined by studying this special case with the tunnel structure buried in the uniform liquefiable sand layer, which was different from the actual

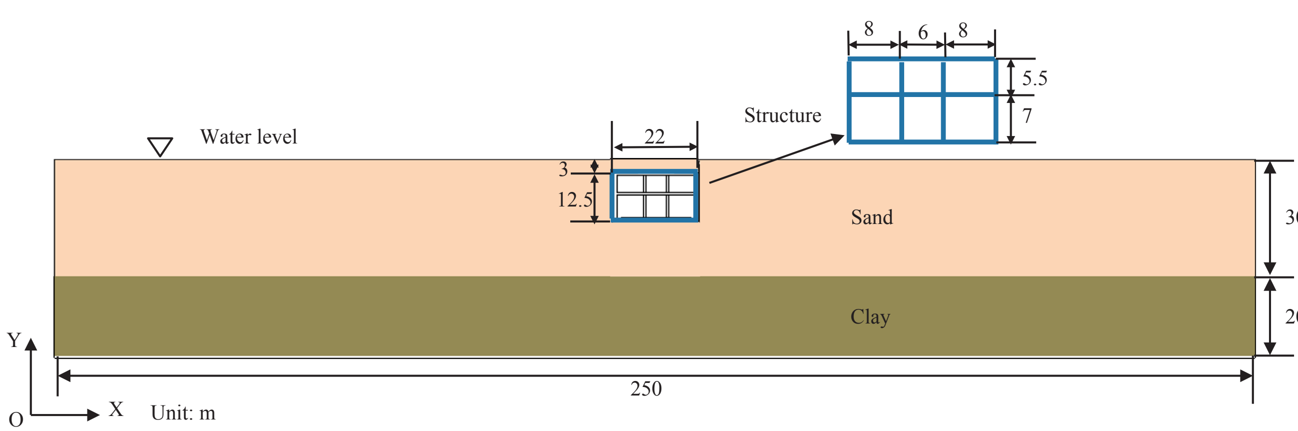

Fig. 2. Computational model and soil profiles.