Tunnelling and Underground Space Technology 69 (2017) 187–202

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

journal homepage: www.elsevier.com/locate/tust

Optimum pattern of ground improvement for enhancing seismic resistance of existing box culvert buried in soft ground

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ARTICLE INFO

Keywords:
Box culvert
Ground improvement
Numerical analysis
Seismic resistance

ABSTRACT

Earthquake is a threat to all kinds of structures including underground structures. Before the 1995 Hyogoken-Nanbu Japan earthquake, however, it was considered that underground structures are at minimum seismic risk in comparison to above-ground structures unless they are crossing the active faults. The collapse of Daikai station in the Kobe subway system during the 1995 Hyogoken-Nanbu earthquake exhibited that underground structures are at high risk of earthquake with shallow overburden. Though researches have been done on this issue, it is still necessary to investigate further the mechanical behavior of underground structure during an earthquake and corresponding efficient seismic enhancement. In this paper, in order to find out an optimum ground-improvement pattern for a rectangular-shaped box culvert constructed in soft ground that does not meet the present seismic requirement, numerical tests with nonlinear 2D/3D dynamic FEM are conducted. Different patterns of the ground improvement for the box curvet constructed with cut-and-cover method are investigated to find out an optimum pattern that can reduce the impact of earthquake in the most effective way. In the 2D/3D dynamic finite element analysis, the ground is Toyoura sand, typical clean sand, and its nonlinear mechanical behavior is described by Cyclic Mobility model. Validity of the proposed numerical method is firstly confirmed with 1 g shaking table test and then numerical tests are conducted to find out the optimum pattern for the ground improvement. Finally, an effective pattern of ground improvement for existing box culvert is proposed by the numerical analysis.

1. Introduction

Underground structures, such as subway facilities, lifelines, warehouses, reservoirs and so on, consist of the major parts of infrastructure for modern society and play an important role in its development. In the design of underground structures, it was considered that underground structures are in minimum seismic risk in comparison to the above-ground structures. The collapse of Daikai station in the Kobe subway system during the 1995 Hyogoken-Nanbu earthquake exhibited that underground structures are also at high risk of earthquake especially those constructed in soft ground with thin overburden. Thereafter, the failure of Bola Highway Tunnel in 1999 Turkey earthquake and failure of gas and water pipelines in 1999 Chi-Chi earthquake in Taiwan clarified that proper consideration of earthquake load in the design of underground structures is also important.

The failures of above-mentioned underground structures give rise to some problems that need to be clarified. The mechanical behavior of underground structure subjected to the earthquake loading is basically a soil-structure interaction problem. Besides, in active seismic region, some existing underground structures do not meet the requirement of present seismic design standard, which becomes a serious problem.

After significant damages were observed in the underground structures in recent earthquakes, e.g., the 1995 Kobe earthquake in Japan, the 1999 Chi-Chi earthquake in Taiwan, and the 1999 Kocaeli earthquake in Turkey, seismic design standards have been revised. NEHRP (National Earthquake Hazards Reduction Program) Recommended Seismic Provisions (2009), FHWA (Federal Highway Administration) Road Tunnel Design Guidelines, and ISO (International Organization for Standardization) 23469 recommended the consideration of seismic load for the design of underground structures.

The mechanical behavior of underground structure subjected to the earthquake loading and the soil structure interaction has been studied by many researchers. For instance, Hashash et al. (2001) reported the seismic design and analysis of underground structures. Ailan and Iwatate (2003) conducted shaking table tests and simulation to analyze the damage mechanism of the subway structure of Daikai station and investigated the dynamic forces acting on the structure due to horizontal sinusoidal and random waves. Gazetas et al. (2005) worked on

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http://dx.doi.org/10.1016/j.tust.2017.06.022
Received 14 March 2016; Received in revised form 23 March 2017; Accepted 20 June 2017
0886-7798/

1999 Athens earthquake records in three underground structures and explained the response of these underground structures through dynamic analyses.

Giannakou et al. (2005) conducted a parametric numerical study and investigated the causes of failure of Bolu tunnel (Düzce, Turkey, 1999). Huo et al. (2005) worked on load transfer mechanisms between underground structure and surrounding ground and evaluated the failure of the Daikai station. Parra-Montesinos et al. (2006) conducted numerical analysis to evaluate the effect of soil-structure interaction on the displacement and the load acting on the RC structure of the Daikai station. Anastasopoulos et al. (2007) conducted a nonlinear analysis to evaluate the response of deep immersed tunnel subjected to strong seismic shaking. Tsinidis et al. (2013) conducted experimental and numerical investigation of the seismic behavior of rectangular-shaped tunnels in soft soils.

The countermeasure against liquefaction for underground structures has also been studied by some researchers. For instance, Yokota et al. (2001) investigated and analyzed the countermeasure against liquefaction at a tunnel near Kitasenju subway station. Schmidt and Hashash (1999) proposed the method for preventing tunnel from flotation due to liquefaction.

Countermeasures to mitigate the seismic destruction of existing underground structures in soft ground should be linked to a real failure happened in the past earthquake. Hence, the failure of Daikai station is selected as a natural large scale experiment in this paper.

The Daikai station was constructed by cut-and-cover method. It consisted of an RC rectangular section with uniformly spaced central columns. During the 1995 Hyogoken-Nambu earthquake the central columns and the ceiling slab were completely collapsed, followed by the settlement of overburden soil around 2.5 m. Based on the works by Iida et al. (1996), the central columns failed first, and then it caused the collapse of the ceiling slab and soil cover settlement. Fig. 1 shows the longitudinal damage patterns to the Daikai station. The severe damage had occurred in the central columns of Section 1. The collapse of the central columns is shown in Photo 1. The columns were poorly reinforced horizontally, resulting in a typical shear failure (Iida et al., 1996). In addition, the design of station in 1962 did not include specific seismic provisions (Hashash et al., 2001).

It is commonly regarded that reducing the earthquake-induced horizontal displacements would make the existing underground structure much safer. The ground improvement method has being developed for years in Japan and has the benefits of short construction time and low construction cost. Thus, the ground improvement method is proposed to reduce the earthquake-induced horizontal displacement as a seismic countermeasure of underground structures.

In this paper, numerical analyses are conducted to evaluate the effect of ground improvement as a seismic countermeasure for existing box culvert in soft soil. Particular attention is paid to finding the most effective and economical type of ground improvement that can reduce the impact of earthquake on the box culvert. Four cases for the analyses are considered. In the numerical analyses, 2D/3D dynamic finite element method (FEM) with the code name of DBLEAVES (Ye, 2007, 2011) is used. In order to evaluate the influence of the soil-structure interaction on the underground structures, a unified system consisted of soil and underground structure is considered. As for the mechanical behavior of soft soil, a nonlinear elastoplastic constitutive model with the name of Cyclic Mobility model (CM model) (Zhang et al., 2007, 2011) is adopted. The concerned underground structure in the analysis is the Daikai station and particular attention is paid to its central columns. The failure of the central columns was the main reason of the structural collapse during the earthquake. In the analyses, the nonlinear behavior of the central columns is modeled with the Axial-force Dependent model (AFD model, Zhang and Kimura, 2002). The CM model and AFD model will be discussed later.

In order to confirm the validity of the proposed numerical analyses, 1 g shaking table test and corresponding 2D dynamic analysis were firstly conducted and the results of both the analysis and the test are compared in detail. Finally, an effective pattern of ground improvement for existing box culvert is proposed by the 3D dynamic FEM that can reduce the effect of earthquake on the box culvert in most effective way.

2. 1g shaking table test and validation of numerical method

In this section, 1 g shaking table test and 2D numerical analysis in the model scale are conducted and the results of both the analysis and test are compared in detail.

The shaking table test device used in the present study is shown in Photo 2. It has the maximum payload, acceleration and displacement of 16 kN, 9.8 m/sec^2 and 0.05 m respectively. The dimension of the shaking table shear box is 1.2 × 1.0 × 0.8 m (length, width and height).

In the model test, the Daikai station is modeled with a similarity ratio of 1/30. The model box culvert is made of iron sheet with a modulus of elasticity of 210 GPa; additionally, in the model the central columns of Daikai station are assumed to be a uniform wall. Photo 3 shows the model box culvert.

The objective of the present model test is not to reproduce the Daikai Station's failure process. Shawky and Maekawa (1996) has published their research on this issue and showed that the resistance of the central columns was smaller than the earthquake loading. The main objective of the present model test is to investigate the accuracy of the numerical method proposed in this paper and to find out the optimum pattern for the partial ground improvement. Therefore, for simplicity the central columns of Daikai Station are considered as a uniform wall.

The similarity law (π theorem) proposed by Iai (1989) is used to determine the scaling factors. However, it is difficult to satisfy all the similarity laws in 1 g model tests; thus, some compromises have to be permitted. In the present study, particular attention is paid to satisfying the similarity ratio of the bending rigidity. The π theories for the model are listed in Table 1.

The similitude factor for the axial rigidity (*EA*) is small, which means that the model is more axially rigid than it needs to be. Instead the similitude factor of bending rigidity (*EI*) is approximately satisfied. The *EA* and the *EI* is the function of wall thickness, elastic modulus, and loading conditions. When the loading is in the axial direction, *EA* has to

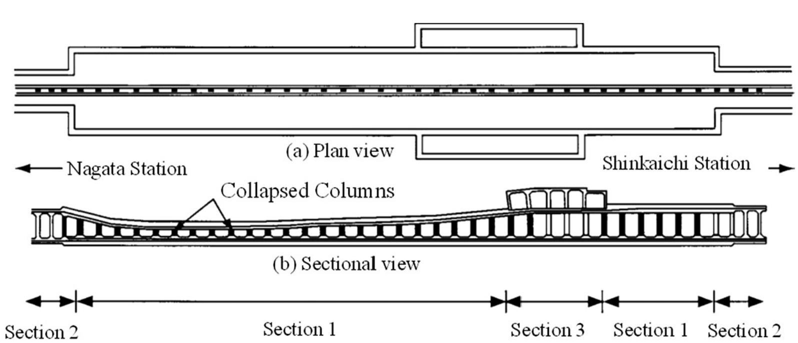

Fig. 1. Damage pattern of Daikai Station (Iida et al., 1996).