Tunnelling and Underground Space Technology 74 (2018) 1–9

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

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

Seismic performance upgrading for underground structures by introducing sliding isolation bearings

Ma Chao[a,b], Lu Dechun[a,*], Du Xiuli[a,*]

[a] Institute of Geotechnical and Underground Engineering, Beijing University of Technology, Beijing, China
[b] School of Civil and Transportation Engineering, Beijing University of Civil Engineering and Architecture, Beijing, China

ARTICLE INFO

Keywords:
Sliding isolation bearings
Underground structures
Collapse mechanism
Deformation capacity
Seismic performance

ABSTRACT

Isolation bearings have been a widely applied seismic strengthening technique in above ground structures. Whereas, the sliding isolation bearings were seldom used in underground structures. This study aims to explore the feasibility of sliding isolation bearings reducing the seismic response of underground structures. The collapse mechanism of underground structures was firstly analyzed by taking the Daikai Station as an example. Numerical results demonstrated that the collapse of the structure was due to the poor ductility of the intermediate columns. Therefore, the sliding isolation bearing could be installed between the columns and the beam to reduce the lateral deformations of columns. In order to determine an appropriate coefficient for sliding bearings, static analyses for the capacity of columns were conducted. Moreover, the performances of a beam-bearing-column system were also investigated. Finally, seismic responses of the underground structure retrofitted with bearings were studied. Numerical results presented that the responses of both columns and the whole structure were reduced remarkably. Moreover, the frictional coefficient of bearing influencing the seismic responses of underground structures was discussed. And some interesting conclusions were also obtained for the seismic design of underground structures.

1. Introduction

The construction of underground structures including subway stations, underground malls, tunnels, and underground parking stations has gained a rapid development in China during recent years. Taking the subway stations as the example, more than 2000 stations along the total of 3000 km long tunnels have been constructed till 2015 (Chen et al., 2016), and up to 373 stations were constructed in 2016. However, almost all the cities with underground structures in China are in the strong earthquake prone area. Seismic investigations showed that underground structures were at greater risk during an earthquake (Sharma and Judd, 1991; Yashida and Nakamura, 1996; Wang et al., 2000; Wang et al., 2009; Shen et al., 2014; Lee et al., 2016). Therefore, it is of urgent need to focus on the seismic safety and seismic design of underground structures.

Seismic isolation technology is an approach that adding an isolation system between structures and the foundation, and is an effective way to reduce earthquake energy transferring from ground to structure (Providakis, 2009; Li and Li, 2011). This technology as an approach to earthquake protection has been used more than 100 years (Buckle and Mayes, 1990) in above ground structures. Seismic isolation technology has been introduced to underground structures aiming to reduce the damage of underground structures during an earthquake (Xin et al., 2014; Li, 2012) in recent years. The isolation layer was applied as the buffering to mitigate the constraint of the surrounding ground, and then the earthquake-induced structural deformation and forces of underground structures were reduced (Xin et al., 2014). The isolation layer was always used for the seismic design of tunnels (Suzuki, 2000; Kim and Konagai, 2001; Konagai and Kim, 2001; Hasheminejad and Miri, 2008; Kiryu et al., 2012; Chen and Shen, 2014; Wang et al., 2017). Moreover, seismic investigations and damage features of tunnels from the Wenchuan earthquake also illustrated that isolation layers could be applied to improve the seismic performance of tunnels (Li, 2012). Studies proved that seismic isolation technology was an effective way of reducing damages to tunnels. Alternatively, seismic reduction technology is another approach to protecting structures surviving during an earthquake, and has also been applied in the underground structures. For example, flexible joints were utilized between the segments of tunnels to mitigate the earthquake-induced stress concentration (Ding et al., 2006; Yu et al., 2013; Do et al., 2015; Kawamata et al., 2016; Yu et al., 2017).

Analyses of seismic responses of underground structures presented

* Corresponding authors.
E-mail addresses: machaowater@126.com (C. Ma), dechun@bjut.edu.cn (D. Lu), duxiuli@bjut.edu.cn (X. Du).

https://doi.org/10.1016/j.tust.2018.01.007
Received 26 April 2017; Received in revised form 2 January 2018; Accepted 5 January 2018
0886-7798/

that intermediate columns were the key structural components (Hashash et al., 2001; Huo et al., 2005; Nam et al., 2016; Ma et al., 2017b). Failure of intermediate columns could result in the collapse of underground structures. Thus, the isolation bearings were also used as the damper installed between the columns and beams to weaken the seismic responses of underground structures. In consideration of the survivability of the Daikai Station from the great lateral deformation, a 3D shock isolator bearing composed of dish spring and lead rubber beading was introduced to reduce the lateral deformation of column (Huan et al., 2011). Numerical results presented that the 3D shock isolator could reduce the lateral deformation and damage of columns. A flexible rubber joint was inserted on upper and/or lower ends of columns to updating the seismic performance of the Daikai station (Mikami et al., 2001). It demonstrated that the induced shear force and moment of columns were also weakened. Similarly, a shear panel damper bearing was installed between the top beam and columns to upgrade the seismic performance of underground structures (Chen et al., 2014). It demonstrated that the maximum shear forces of columns in both single- and double-story structures declined effectively although the lateral deformation of columns increased. However, during the studies of Mikami et al. (2001), Huan et al. (2011) and Chen et al. (2014), the lateral deformation of columns changed slightly during earthquake. Because the functionality of columns is to bear vertical loadings, more effective measures which could keep the columns standing upright, should be ultimate to reduce the deformation of columns and to promote the seismic responses of underground structures.

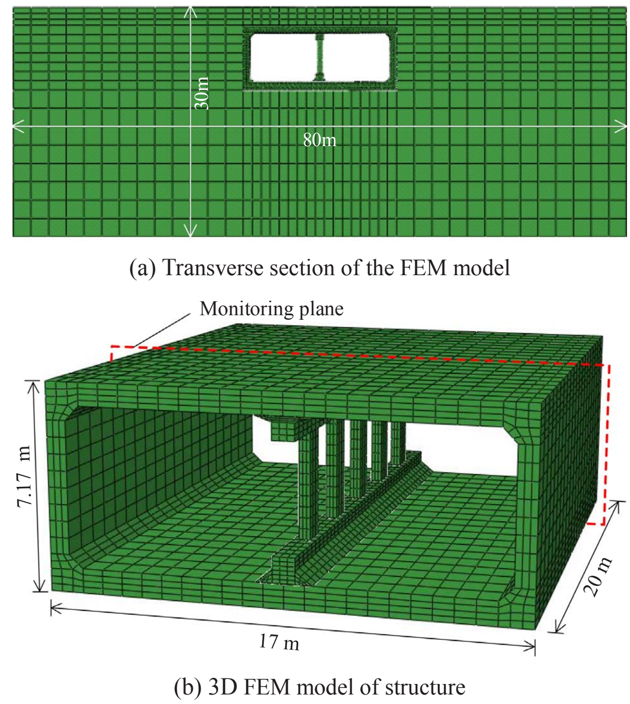
Sliding isolation bearing is a typical type of passive seismic isolation devices. Sliding isolation bearings are capable of changing stiffness property during the horizontal flexibility. The bearings provide protection against earthquakes by reducing the peak and residual displacement of buildings (Nagarajaiah et al., 1993; Mualla and Belev, 2002; Fenz and Constantinou, 2006; Castaldo et al., 2015). When the bearings are installed between beams and columns of underground structures, the deformation of columns will be transferred to the slide of the bearings. Therefore, in this study, sliding isolation bearings were utilized to underground structures for updating the seismic response. The collapse mechanism of underground structures was firstly analyzed by taking the Daikai Station as an example. Then the recommended optimum range of the frictional coefficient of sliding isolation bearings was determined by carrying out the ductility of columns under different normalized force. To assess the seismic performance of underground structures retrofitted with sliding bearings, nonlinear dynamic analyses were conducted, and a discussion about the seismic improvement of underground structures was also presented, which may be a useful references for future design.

2. Failure mechanism of underground structures

2.1. Target structure and numerical model

During the Great Hanshin earthquake, on 17 January 1995, more than 30 intermediate columns (in total 35 columns) of the Daikai Station completely collapsed over a total length of about 110 m. The largest subsidence of the ground reached 2.5 m. This station is the only collapse underground structure during an earthquake. The collapse of the Daikai Station attracted great interest of researchers and engineers, and this station was always represented as an example to study the failure mechanism of underground structures (Iida et al., 1996; Yashida and Nakamura, 1996; Hashash et al., 2001; Huo et al., 2005).

In this section, the completely collapse section of the Daikai Station is selected as the research target to study the collapse mechanism of underground structures. Then a 3D FEM model with dimensions of 80 m long, 20 m width and 30 m high was built for the nonlinear numerical analysis, as shown in Fig. 1. According to Liao's (2013) study, the maximal height of element h_{max} of the shear motion propagating in the



(a) Transverse section of the FEM model

(b) 3D FEM model of structure

Fig. 1. FEM numerical model.

soil should be determined by

$$h_{max} = (1/75 \sim 1/160)V_s/f_{max} \tag{1}$$

where, V_s is the shear and compression motion velocity, which can be deduced by Eq. (2).

$$G = \rho V_s^2 \tag{2}$$

where, ρ is the density of the soil. f_{max} is the maximal vibration frequency of the input motion, which is 0.82 Hz. The viscoelastic artificial boundary conditions were utilized to deal with the lateral and bottom boundaries in order to decrease the influence caused by infinite field. On the basis of the viscoelastic boundary condition, the wave field decomposition method was used to implement the seismic input. During the simulation, the horizontal and vertical components of ground motions shown in Fig. 2 were applied, which were measured at the Kobe meteorological observatory closing to the Daikai Station. Noting that, both the horizontal and vertical components of ground motion are at a very high level. However, the amplitudes of both ground motions decrease to no larger than 0.1 g after 20.0 s. Therefore, a period of the previous 23.0 s simulation was carried out.

The concrete in the structure was modeled as the plastic damage model, with density 2500 kg/m^3, Poisson's ratio 0.2, Young's modulus 30 GPa, initial compression yield stress 18.8 MPa, limited compression yield stress 26.8 MPa, and initial tensile yield stress 2.4 MPa. An elastoplastic constitutive model developed for soil (Lu et al., 2017; Ma et al., 2017a,b) was used to describe the 3D strength, strain softening and the behaviour under monotonic and cyclic loading, with the density $\rho = 1900$ kg/m^3, frictional angle $\varphi = 35°$, Poisson's ratio $\upsilon = 0.3$, initial pore ratio $e_0 = 0.6$, the isotropic compression index $\lambda = 0.12$ and the swelling index $\kappa = 0.008$. The initial consolidation pressure p_0 of ground increases from 1.5 MPa at the surface to 3.0 MPa at the bottom. For the soil, the Yong modulus E is expressed as:

$$E = 3(1-2\upsilon)\frac{1+e_0}{\kappa}p_0 \tag{3}$$

And $G = E/2(1 + \upsilon)$. Then according to Eqs. (1)–(3), the range of the maximal element height h_{max} of the soil can be deduced as 2 m–4 m for the ground surface and 4 m–8 m for the bottom. Here, the lower