Effect analysis of burial depth on seismic dynamic response of metro station structure

Shuai Huang^{1,*}, Yuejun Lyu¹, Liwei Xiu¹ and Zhen Xu²

¹ Institute of Crustal Dynamics, China Earthquake Administration, Beijing 100085

² Beijing Key Laboratory of Urban Underground Space Engineering, School of Civil and Resource Engineering, University of Science and Technology Beijing, Beijing, China

Abstract. In this article, based on the nonlinear elastic-plastic finite element model for metro station, considering the structure-soil dynamic interaction, the influence laws of the burial depth on the dynamic response and failure mode of the metro station structure under near and far-field earthquakes are studied. We found that the influence of burial depth on the deformation of the metro station may be omitted after a specific value of the burial depth. With the increasing of the burial depth, the acceleration dynamic amplification factors of the metro station structure decreases. At last, indoor shaking table test for metro station was done, through which we determined the position of initial failure and the failure mode of the metro station structure under earthquake.

1 Introduction

Metro stations are located on urban trunk roads or in urban residential areas, business districts or the most populous areas in general. In case of a devastating disaster, it may generate a chain and scale effect, leading to aggravated hazards and a series of very serious infrastructure damages, such as cracking of neighboring buildings and rupture of underground pipelines. In recent years, seismic actions have triggered damage of a great many underground structures^{[1][2]}. For ground structure, the changes in natural vibration characteristics, have large influence on structure response; for underground structure, the dynamic characteristics of the foundation is a major factor influencing structure response, so it is unreasonable to consider static method as a basis of the seismic design of underground structure^[3]. China is relatively backward in seismic research of underground structure and still does not have a sound seismic analysis method for underground structure by now, so further research and development is needed in the seismic design theories and methods regarding to underground structure.

The dynamic characteristics of underground structure are controlled by the surrounding foundation soil. Meanwhile, foundation soil is also influenced by underground structure, so it is necessary to take account of the interaction between soil and structure^[4]. Hashasha^[5] pointed out that when underground structure shakes at a low level under low-intensity seismic action or is in hard rock or other media, the results calculated by quasi-static method are acceptable. Otherwise, the influence of structure-soil interaction on underground structure should not be neglected. G.Gazetas^[6] studied

the influence of structure-soil interaction on the dynamic response of underground structure under seismic action, and concluded that the influence of structure-soil interaction on underground structure cannot be neglected. Youssef M.A. Hashasha^[7] stated that when underground structure shakes at a low level under low-intensity seismic action or is in hard rock or other media, the results calculated by quasi-static method are acceptable. Otherwise, the influence of structure-soil interaction on underground structure should not be neglected. Although some studies have been conducted on seismic dynamic response of metro stations, most of them are concentrated on single aspect and seldom consider the influence of multiple factors on the dynamic response of the metro station. Particularly, fewer studies were made with regard to the influence of burial depth on the failure mode of the metro station by indoor shaking table test. Besides, the current domestic codes for seismic design only provide some principled provisions on the seismic design of metro^{[8][9]}, and lack systematic and perfect design theories and methods. In this regard, this article established a nonlinear elastic-plastic finite element model for metro station structure based on soil-structure interaction, and we studied the influence laws of interlayer on seismic dynamic response of metro station under near and far-field earthquakes, and analyzed the dynamic damage and failure mode of metro station through an indoor shaking table test. Thus, we expected to provide reference and guidance value for engineering practice by obtaining some basic laws of metro station under seismic action.

* Corresponding author: huangshuai3395@163.com

2 Calculation Model

2.1 Establishment of a Numerical Simulation Model

A rectangular metro structure was selected as a research object. The metro station structure is 22m wide, 15m high and 1m thick, the calculation area of the structural part is 22m×15m, and the burial depth of the station is 20m. The artificial boundary of the calculation site is twice of the width of the metro structure. The distance of the artificial boundary from a bottom side to a bottom side of the metro station is 25m, in other words, the width is 110m and the depth (including structure) is 60m. The metro structure was treated as single-phase medium. The soil constitutive model adopted Mohr-Coulomb, the station structure adopted a linear elastic constitutive model, and meanwhile Rayleigh damping was selected

to simulate damping effect [10]. Soil and metro station structure both adopted rectangular grid 1m×1m adopted by the plane strain unit to conduct discrete operation. The left boundary, right boundary and bottom boundary of the model all adopted free field boundaries. The numerical simulation model for metro station are as shown in Figure 1. Physical parameters of site soil and station structure are as shown in Table 1.

Fig.1. Numerical model and monitoring numbers of metro station

Table 1. Physical and mechanics parameters

Name	Density(kg/m ³)	Modulus of Elasticity (GPa)	Shear modulus (GPa)	Poisson's ratio	Cohesion (kPa)	Internal friction angle(°)	Yield strength (N/mm ²)
Site soil	2100	0.54	0.36	0.25	44	27	\
Interlayer	2650	0.01	0.004	0.3	10	15	\
metro station structure	2500	17.3	11.5	0.20	\	\	10

2.2 Selection of Seismic Waves

The site for metro station is set as type II site. The article referred to the seismic waves recommended in Japanese road specification. It takes site type into account and meanwhile considers that seismic waves are inputted from foundation bottom. Therefore, this article referred to Japanese *Specification for Highway Bridges* [21]. Seismic fortification intensity is scale VIII, and design basic seismic acceleration value is 0.2g, as shown in Figure 2.

Fig.2. Time history of seismic wave

3 Influence law of burial depth on dynamic response of the metro station

We chose roof position as a calculation point and carried out calculation at four burial depths of the metro station: 10m, 15m, 20m and 25m. We extracted the maximum horizontal displacements of the roof and side walls of the metro station, as shown in Figure 4 and Figure 5.

(a) T1-II-1

(b) T2-II-1

Fig.4. The maximum horizontal displacement of the roof of metro station under near and far field earthquake

Fig.5. The maximum horizontal displacement of the side wall of metro station under near and far field earthquake

As shown in Figure 4 and Figure 5, we may know that, with the increase of the burial depth of the metro station, the horizontal displacements of the roof position and side wall position show a decreasing trend under T1-II-1 and T2-II-1 earthquakes, indicating that the larger the burial depth of the metro station is, the less the deformation will be, and more stable the metro station will be under seismic action. When the burial depth reaches 20m, its influence on the deformation of the metro station structure will decrease with the increase of the burial depth. Thus, in a specific range of burial depth, the burial depth of the metro station has large influence on the deformation of station structure. After a specific value of the burial depth, the influence of burial depth on the deformation of the metro station may be omitted.

The maximum horizontal acceleration dynamic amplification factor of the metro station is as shown in Figure 6 and Figure 7.

Fig.6. The maximum horizontal acceleration dynamic magnification factors of the roof of metro station under near and far field earthquake

Fig.7 The maximum horizontal acceleration dynamic magnification factors of the side wall of metro station under near and far field earthquake

As shown in Figure 6 and Figure 7, we may know that with the increase of the burial depth of the metro station, the acceleration dynamic amplification factors of the roof position and side wall position are on a decreasing trend under T1-II-1 and T2-II-1 earthquakes. Thus, the increase of the burial depth of the metro station may alleviate the vibration effect of the metro station structure under seismic action. Near-field earthquake has greater influence on the dynamic amplification factor of the metro station structure than that under far-field earthquake.

4 Conclusions

(1) When the burial depth of the metro station increases gradually, the displacement and acceleration amplification factor of the metro station structure show a decreasing trend. When the burial depth reaches a specific value (the depth in this article is 20m), with the continued increase of burial depth, its influence on displacement and acceleration amplification factor of the metro station structure decreases.

(2) After a specific value of the burial depth, the influence of burial depth on the displacement and acceleration amplification factor of the metro station could be omitted.

(3) Near-field earthquake has greater influence on the displacement and dynamic amplification factor of the metro station structure than that under far-field earthquake.

Acknowledgments

This work is financially supported by the National Natural Science Foundation of China (Grant No.

51708516), National Key R&D Program of China (2017YFC1500404), research grant from Institute of Crustal Dynamics, China Earthquake Administration (No. ZDJ2019-10) and the Fundamental Research Funds for the Central Universities (FRF-BD-19-004A).

References

1. Quan Dengzhou, Wang Yihong, Jing Yanlin, Zhou Shenhua and Zhang Youchao. Review of Anti-Seismic Structures of Subway in Loess Area [J]. Technology for Earthquake Disaster Prevention, 2015, 10(3): 565-574.
2. Du Xiuli, Wang Gang, Du Dechun. Earthquake damage mechanism analysis of DaKai Metro Station by kobe Earthquake[J]. Journal of Disaster Prevention and Mitigation, 2016,36(2):166-171.
3. Ou Yang Yanqing , Ma Shicheng. Dynamic Response Analysis of Underground Structures Subjected to Earthquakes Occurring Directly Beneath the Structure[J]. Soil Engineering and Foundation, 2009, 23(6):68-70.
4. Li Xiaoyun. The Response Characteristic Research of Shallow-tunnel Timbering Structures under Earthquake Loads[D]. Xi'an University of Science and Technology, 2011.
5. Hashash Y, Hook J J, Schmidt B. Seismic design and analysis of underground structures[J]. Tunnelling and Underground Space Technology, 2001, 16(4):247-293.
6. G.Gazetas, N. Gerolymos, I. Anastasopoulos. Response of three Athens metro underground structures in the 1999 Parnitha earthquake[J]. Soil Dynamics and Earthquake Engineering, 2005(25): 617-633.
7. Youssef M.A. Hashasha, Jeffrey J. Hooka, Birger Schmidtb, John I-Chiang Yaoa. Seismic design and analysis of underground structures[J]. Tunnelling and Underground Space
8. GB 50157-2013.Code for design of Metro[S]. Beijing: China Architecture & Building Press.
9. GB 50010-2010.Code for design of concrete structures[S]. Beijing: China