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Influence of the diaphragm wall on the earthquake responses of the underground station structure under two different connection types

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ABSTRACT: Two types of connection methods are often used to connect the diaphragm wall with the side wall of underground subway station. In this paper, the different seismic response of underground subway station caused by different connection types is studied by the finite element method. As a result, the connection types between the diaphragm wall and the subway station have great influence on the seismic response of the underground station structure, such as the interlayer displacement angles, the lateral displacement response, the seismic damages of structure, and so on. The tie connection type should greatly increase the lateral resisting stiffness of the underground subway station, which should alleviate its seismic damages as a whole. However, the tie connection type should also aggravate the earthquake damages of the top and bottom plates near to the side wall. The above findings should be recognized in the seismic design of underground subway station.

1 INTRODUCTION

Due to the subway station buried in the soils completely, it has been generally thought that its seismic performance is better than those of the above-ground structures. The seismic collapse of Dakai subway station in the Great Hanshin Earthquake in 1995 was a wake-up call (Iwatate et al. 2000; Hashash et al. 2001), which have attracted the attention of scholars on the seismic performance of underground structure. However, due to the complex interaction between the soil and underground structure, the research on the seismic response mechanism of underground subway structures is still in its infancy, and the earthquake damages of the large underground structure should be studied fully at present.

The underground diaphragm wall, which is used for the pit excavation and support system in the early construction stage of underground subway station, is often used as part of the side wall of the subway station structure in permanent stage. The connection type between the diaphragm wall and the side wall of underground subway station can be divided into the tie connection type and the slip connection type. The tie connection type does not allow the slipping and separating of the diaphragm wall from the side wall of underground subway station, but the slip connection type support the slipping and separating of the diaphragm wall from the side wall of underground subway station.

Existed studies on the earthquake responses of underground structure have shown that the existence of diaphragm wall will change the displacement field of the soil around the subway station (Zhuang et al. 2019). At the same time, the connection type between the diaphragm wall and the side wall of the station will have an important impact on the lateral stiffness of the subway station and the deformation of the surrounding soils, which should also change the deformation characteristics and failure mode of the underground subway station. However, there is no clear suggestion about the influence of diaphragm wall on the earthquake responses of the subway station in the current seismic code for the underground structures or studies on the seismic performance of underground structure (Chen et al. 2013; Chian et al. 2015; Pitilakis et al. 2014). Zhuang et al. have used software Abaqus to simulate the effect of the diaphragm wall on the seismic response of subway station structure with tie connection type (Zhuang et al. 2019), but not yet demonstrated the influence of different connection type on the dynamic characteristics and earthquake failure modes of underground subway station.

In summary, this paper takes the actual subway project as the engineering background, the nonlinear static-dynamic coupling analysis model to simulate the interaction among the subway station and the diaphragm wall and the soils is established by using the commercial finite element software Abaqus, and the influences of different connection type on the interlayer displacement angle, the lateral relative displacement response and the seismic damage characteristics of underground subway station structure are analyzed in detail (Zhuang et al. 2019). Some findings and conclusions in this study can provide valuable references for the seismic analysis and the seismic design of underground structure including the effect of the diaphragm wall.

2 FINITE ELEMENT MODELS

2.1 *Dynamic constitutive model of soil and concrete*

The stress-strain relationship of soils is simulated by the memory visco-plastic nested surface dynamic constitutive model developed by Zhuang (2006, 2009), which has been verified by the tests and successfully used in the earthquake responses of the underground structures. According to the selected site conditions of a subway underground station in Nanjing city, the main model parameters of soil are shown in Table 1.

The strength of concrete for the underground station structure is C30. The visco-plastic dynamic damage model proposed by Jeeho et al. in 1998 is adopted to simulate the nonlinear earthquake damages of the reinforced concrete. Based on the fracture energy principle of concrete, this model is improved on the basis of the plastic damage model proposed by Lubliner et al. (1989). Two damage variables are used to describe the different stiffness attenuation laws of concrete under tensile and compressive failure. Several hardening variables were used to modify the yield function of the model, and the dynamic plastic damage constitutive model of concrete under cyclic loading was established. The corresponding parameters of the dynamic damage model of C30 concrete can be found in literature (Zhuang et al. 2016). The damping of the above materials is approximated by the Rayleigh damping method.

Table 1. Geological conditions and physical parameters of the soils

Layer number	Soil	Unit Weight ($kN{\cdot}m^{-3}$)	Elastic Modulus MPa	Layer thicknessm	Dynamic Poisson ratio	CohesionkPa	Internal friction angle (°)	Shear wave velocity (m/s)
1	Prime fill	18.4	8.0	3	0.45	13.5	16	140.0
2	Soft clay	19.0	10.0	6	0.35	15.4	26	152.7
3	Fine sand	20.5	14.5	6	0.30	7.0	30	167.1
4	Clay	19.4	12.0	8	0.45	18.8	16	158.5
5	Medium sand	20.9	21.0	7	0.30	5.0	28	172.7
6	Medium sand	21.2	27.8	10.75	0.32	5.0	30	205.8
7	Silty clay	18.9	33.0	10.75	0.30	12.3	28	236.3
8	Sandy soil	20.5	29.0	13.5	0.32	6.2	30	263.2
9	Old clay	19.3	35.0	15	0.42	21.0	21	491.6

2.2 *Dynamic contact between soil and concrete*

The dynamic contact between the soil and the subsurface of underground structure defines the mechanical transfer characteristic of the contact surface force transfer, and the contact equation is solved by the contact algorithm. The contact method used in software Abaqus is suitable for simulating the large sliding on the contact surface and continuous transformation of the contact surface between separation and closure. In this paper, the normal contact on the contact surface all adopt the "hard" contact method, and the contact surface will be immediately separated when tension occurs between soil and underground structure, and then it should contact again when the compress force takes place again. The tangential contact obeys the Coulomb's law of friction. When the shear stress on the contact surface is greater than the maximum friction limiting of the contact surface, the soil will produce tangential sliding relative to the underground structure. For the subway station with slip connection type, the friction coefficient μ= 0.55 (Chen et al. 2014). For the subway station with the tie connection type, the connection between the diaphragm wall and the side wall of underground structure is no relative displacement and separate during the whole process of earthquake process.

2.3 *Input ground motion*

The seismic waves used in this paper are Kobe wave and El-Centro wave. Kobe wave is the strong ground motion recorded by the Kobe Ocean Meteorological Observatory during the 1995 Kobe Earthquake in Japan. In this paper, the North-South horizontal acceleration record is taken as the input wave from the bedrock, which original peak acceleration of the Kobe wave is 0.85 g, and its duration of the strong earthquake part is about 10 s. The El-Centro wave is a strong ground motion recorded during the 1940 Imperial Valley earthquake in the United States, which original peak acceleration of the wave is 0.349 g, and the duration of the strong earthquake part is about 26 s. The time history and Fourier response spectra of the two earthquake waves are shown in Figures 1-2 respectively. When the seismic wave is input on the horizontal bedrock, its peak accelerations are adjusted to 0.05 g, 0.1 g, 0.2 g, 0.3 g and 0.4 g respectively, and which whole durations are all adjusted to 40 s.

2.4 *Effect of the initial geostatic stress*

For the underground structure completely buried in the soil, the initial geostatic stress state of the surrounding near-field soils are obviously different from those of the far-field soils. The initial stress state of the surrounding soil obviously has a great influence on the dynamic characteristics of the soft soil, which in turn has an important influence on the dynamic response of the underground structure. Therefore, it is necessary to consider the influence of the initial geostatic stress conditions on the soil-structure interaction system. In view of this, Zhuang et al. in 2011 have established the finite element analysis method to simulate the static-

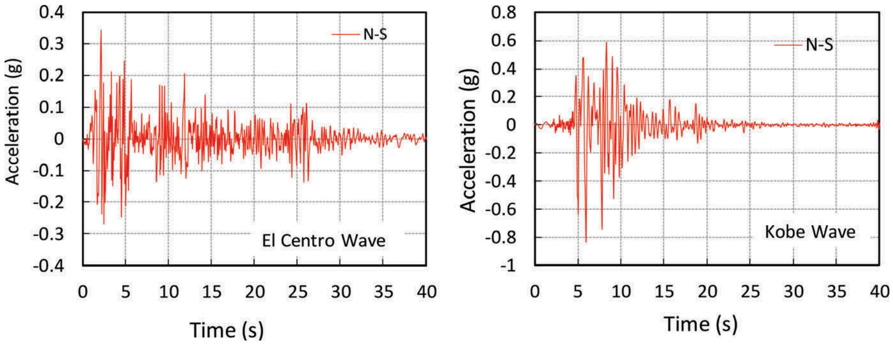


Figure 1. Selected accelerograms in this study

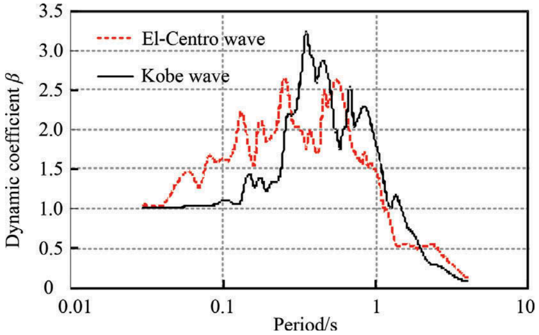


Figure 2. Acceleration response spectra of the two earthquake waves normalized by the initial value

dynamic coupling nonlinear interactions between the soil and underground structure. In this analysis method, the specific initial geostatic stress is carried out from the site initial geostatic equilibrium analysis before the dynamic analysis step. According to the geostatic stress state at the integral point of the soil element, the following formula is used to calculate the initial dynamic shear modulus of the soil in the dynamic analysis step

$$G_{d0} = \rho V_s^2 \left(\frac{p}{p_0}\right)^{0.5} \tag{2}$$

$$p = \frac{\sigma_1 + \sigma_2 + \sigma_3}{3} \tag{3}$$

In the formula, G_{d0} is the initial dynamic shear modulus of the soil, ρ is the soil density, V_s is the shear wave speed of the soil, p is the effective mean stress,p_0 is the confining pressure corresponding to the position in the free layer soil layer, (σ_1, σ_2, σ_3) is the stress state corresponding to the soil element integration point.

2.5 *Finite elements of the soil-structure interaction model*

The initial geostatic stress condition is recorded in the static analysis step. When the finite element calculation and analysis are transferred from the static analysis step to the dynamic analysis step, the lateral boundary conditions of the model foundation must be converted. In the analysis model, the horizontal boundary of the static analysis step adopts the horizontal constraint and the vertical free roller boundary, and the bedrock surface adopts a fixed constraint. In the dynamic analysis step, the boundary conditions are transformed into the vertical constraint of the lateral boundary and the free roller boundary. The bedrock surface is horizontally input to the ground motion and vertical constraint. The width of the model foundation is 200 m and its thickness is 80 m. According to the study of Lou et al. in 2000, when the width of the whole soil foundation is greater than 5 times that of the structure, the influence of the boundary on the dynamic response of the structure can be neglected.

Based on the above modeling method and the connection between diaphragm wall and subway station structure, the finite element analysis model established is shown in Figure 3. The soil is discretized by four-node plane reduced integral element, and the station structure and diaphragm wall are discretized by four-node plane integral element. The reinforcement in station structure and diaphragm wall is modeled by implantation method. The reinforcement is discretized by equivalent two-dimensional beam element. The characteristic length of soil element varies from 1 m to 2 m. When the subway station structure is equivalent to the plane strain problem, the method of reducing the elastic modulus with the same stiffness is adopted to consider the influence of the plane strain element simulating the three-dimensional middle

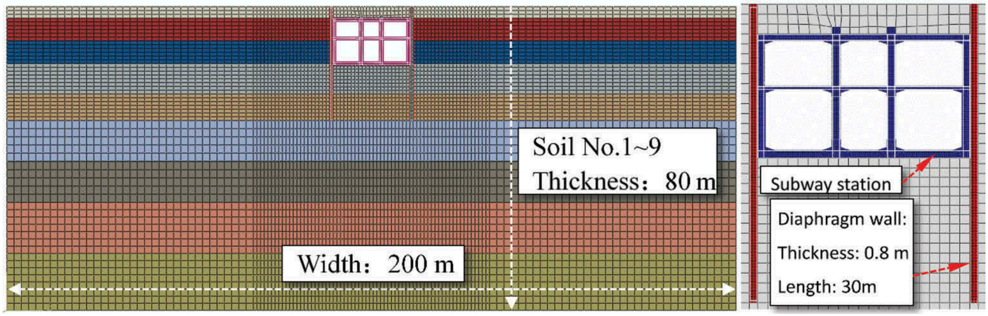


Figure 3. Schematic diagram of finite element model

column, and the circular middle column is equivalent to the continuous wall with the thickness of 0.8 m.

3 ANALYSIS ON THE RESULTS

3.1 *Lateral deformation of underground structure*

Figure 4 shows the maximum inter-story displacement angles of the underground structure changing with the PGA of input modtion. It proves that the effect of the connection type on the inter-story displacement angle of the under layer of underground structure is greater than the effect on those of the upper layer of underground structure. As a result, to the upper layer of underground structure, which inter-story displacement angles with the tie connection type are smaller than those with the slip connection type, especially for the EL Centro wave inputted. Meanwhile, the inter-story displacement angles of the upper layer should also larger than those of the under layer of underground structure.

The connection type should change the dynamic interaction between the diaphragm wall and the underground structure, and then changes the lateral deformation of underground structure. Figure 5 shows the maximum lateral displacement along the structural height. It proves that the lateral displacement curves under the two different connection types are very close when the input peak acceleration is small (0.05 g, 0.1 g). However, with the increase of the input peak acceleration, the effect of connection type also becomes stronger, especially on the shape of the maximal lateral displacement curve. As a result, the shape of lateral displacement curve should be close to a straight line under the tie connection type, but it should be close to a sine curve under the slip connection type. According to above finding, the effect of the connection type between the diaphragm wall and the underground structure should be

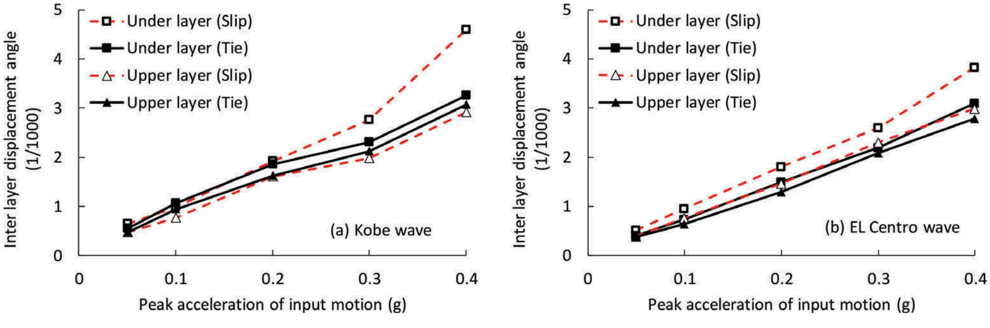


Figure 4. Maximum interlayer displacement angles of the subway station

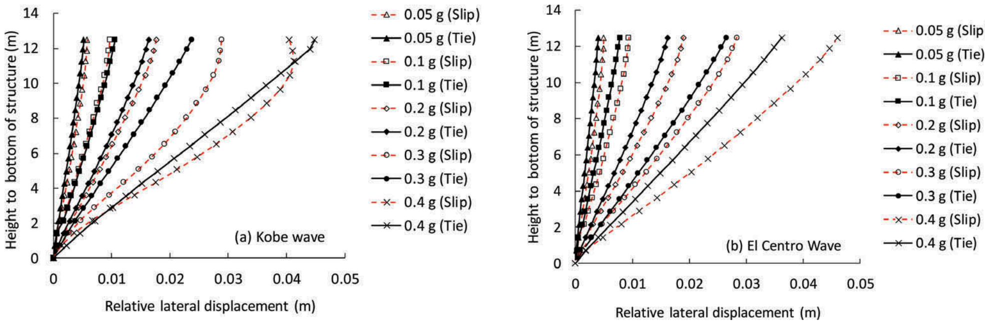
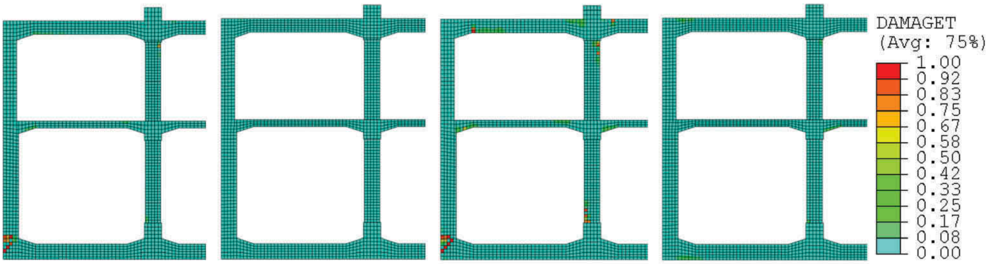


Figure 5. Maximal lateral displacement curves of underground subway station

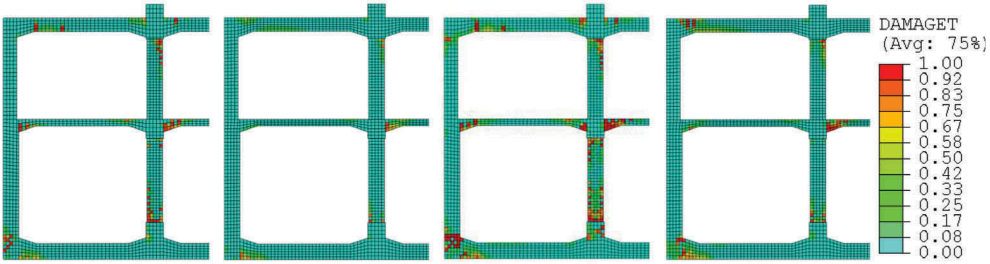
considered in the response displacement method for the seismic design of underground structure, in which the lateral displacement curve of underground structure has been looked as a sine curve (Hashash et al. 2001).

3.2 *Seismic damage of underground structure*

In order to further study and analyze the influence of different connection type on the seismic performance of underground structure, Figure 6 shows the damage cloud diagram of the underground structure when the Kobe wave is inputted from the bedrock. It should be noted that the tensile failure factor (DAMAGET in Figure 6) have appeared on the concrete structure when the tensile damage factor is greater than zero ($d_t > 0$), and the concrete has been damaged completely by the tensile stress after $d_t \geq 1$. As for the compression damage (DAMAGEC in Figure 7), the concrete is expected to be damaged after $d_c > 0$ and cracked after d_c1 (Analysis user's guide Volume □: Materials, Abaqus 6.13). The steel rebar is assumed to be an elastic material with an elastic modulus of 210 GPa.

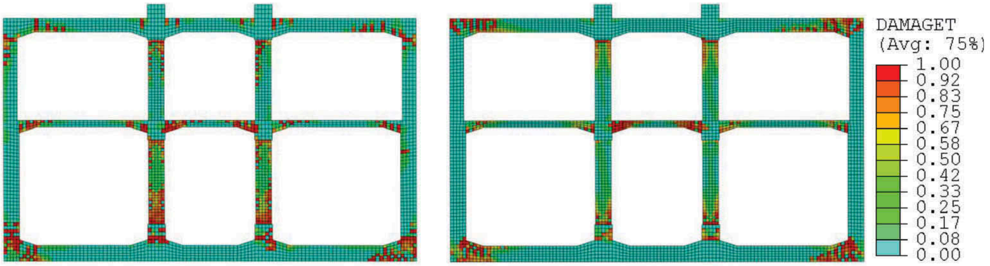


（a）Slip (0.05 g) （b）Tie (0.05 g) （c）Slip (0.1 g) （d）Tie (0.1 g)



（e）Slip (0.2 g) （f）Tie (0.2 g) （g）Slip (0.3 g) （h）Tie (0.3 g)

Figure 6. Tensile damage cloud of underground subway station with inputting Kobe wave



(i) Slip (0.2 g)　　(j) Tie (0.2 g)

Figure 7. Compress damage cloud of underground subway station with inputting Kobe wave

As shown in Figure 6, when the input peak acceleration is 0.05 g, the bottom of the side wall of the subway station structure has been severely damaged under the slip connection type, but there is no obvious damage to the tie connection type. When the input peak acceleration increases to 0.1 g, the damaged of underground structure under the slip connection type is more serious than that with input peak acceleration being 0.05 g, but it has not be found on the underground structure under the tie connection type. When the input peak acceleration increases to 0.2 g, the tensile damages have been found at almost joints of underground structure under the slip connection type, and only slight tensile damages have been found under the tie connection type. When the input peak acceleration continued increases to 0.4 g, the tensile damages of the columns of subway station under the slip connection type are much greater than those under the slip connection type.

The above analysis results show that the subway station structure under the different connection types have completely different seismic tensile damages. The existed studies have shown that the severe seismic damages of the columns should be the greatest and main inducement to the seismic collapse of underground subway station structure. To this view, the adoption of tie connection type can improve the seismic performance of underground subway station structure. However, under the strong earthquake, the damage degree of the slab end of the subway station structure under the tie connection type is obviously greater than that under the slip connection type. Under the tie connection type, the diaphragm wall have a significant effect on the seismic deformation of the joint between the slabs and the side wall of underground structure. Under the same relative lateral deformation, the deformation of the side wall of the underground structure under the tie connection type is severely limited by the diaphragm wall, which leads to the deformation increase of the slabs near to the joints. As a result, the tensile damage of the slabs near to the side wall should be more serious.

Due to the compress damage has not been found when the input peak acceleration are 0.1 g and 0.2 g, Figure 7 only shows the compress damages of the underground structure when the input peak acceleration are 0.3 g and 0.4 g. The compress damages only found at the ends of the columns. Meanwhile, the compress damage is also more severe than that under the tie connection type, especially when the peak acceleration of the input ground motion increases to 0.4 g. The above found show that the diaphragm wall will share the vertical load with the underground structure under the tie connection type due to the tangential force transmitting on the connection surface.

4 CONCLUSIONS

In view of the two different connection types between the diaphragm wall and the side wall of underground structure, the finite element analysis model for the nonlinear dynamic interaction system of the soil-diaphragm wall-underground structure is developed in this study. The influence of the connection type on the seismic response and damage of the underground subway station structure was analyzed. The main findings and conclusions obtained are as follows:

1. The tie connection between the diaphragm wall and the side wall will obviously increase the lateral stiffness of the underground subway station structure, and then reduce its lateral displacement response amplitude. Especially, when the input peak acceleration is larger, the influence of the connection type should be greater.
2. The shape of lateral displacement curve should be close to a straight line under the tie connection type, but it should be close to a sine curve under the slip connection type. As a result, to the response displacement method for the seismic design of the underground structure, the effect of the connection type between the diaphragm wall and the underground structure should be considered to decide the lateral displacement curve of underground structure.
3. If the tie connection type is adopted in the design of the underground structure, the seismic damage of column and side wall are obviously weaker than those under the slip connection type. With the peak acceleration of input ground motion increasing, the effect of diaphragm wall on reducing the seismic damages of underground structure is more obvious. However, the tie connection type should aggravate the seismic damages of slabs near to the side wall. To the earthquake-resistance design of underground structure, the tie connection type should be more benefit on the seismic performance of underground structure.

REFERENCES

Chen, F.Q. & Tian, W. & Liu, Z.G. et al. 2014. Experimental study on friction coefficient of concrete with matching pouring surface. *China Harbour Engineering* 202(12): 34–38.

Chen, G.X. & Wang, Z.H. & Zuo, X. et al. 2013. Shaking table test on the seismic failure characteristics of a subway station structure on liquefiable ground. *Earthquake Engineering & Structural Dynamics* 42 (10): 1489–1507.

Chian, S.C. & Madabhushi, S.P.G. 2012. Effect of buried depth and diameter on uplift of underground structures in liquefied soils. *Soil Dynamics & Earthquake Engineering* 41: 181–190.

Hashash, Y. & Hook, J. & Schmidt, B. et al. 2001. Seismic design and analysis of underground structure. *Tunneling and Underground Space Technology* 16(4): 247–293.

Iwatate, T. & Kobayashi, Y. & Kusu, H. et al. 2000. Investigation and shaking table tests of subway structures of the Hyogoken-Nanbu earthquake. *The 14th World Conference on Earthquake Engineering*. Beijing, Paper No.1043.

Lee, J. & Fenves, G.L. 1998. Plastic-damage model for cyclic loading of concrete structures. J*ournal of Engineering Mechanics* (4): 892–900.

Lou, M.L. & Wang, W. J. & Zhu, T. 2000. Soil lateral boundary effect in shaking table model test of soil–structure system. *Earthquake Engineering and Engineering Vibration* 20(2): 30–36. (in Chinese)

Lubliner, J. & Oliver, J. & Oller, S. et al. 1989. A plastic-damage model for concrete. *International Journal of Solids and Structures* 25(3): 299–326.

Pitilakis, K. & Tsinidis, G. 2014. Performance and Seismic Design of Underground Structures. In M. Maugeri & C. Soccodato (ed.) *Earthquake Geotechnical Engineering Design: Geotechnical, Geological and Earthquake Engineering*, Springer, Cham.

Zhuang, H.Y. & Cheng, S.G. & Chen, G.X. 2008. Numerical emulation and analysis on the earthquake damages of Dakai subway station caused by the Kobe earthquake. *Chinese Journal of Rock and Soil Mechanics* 29(1): 245–250.

Zhuang, H.Y. & Wu, X.Z. 2011. Study on the soil-underground structure static & dynamic coupling nonlinear interaction. *Chinese Journal of Rock Mechanics and Engineering* 30(s1): 3112–3119.

Zhuang, H.Y. & Hu Z.H. & Chen, G.X. 2015. Numerical modeling on the seismic responses of a large underground structure in soft ground. *Journal of Vibroengineering* 17(2): 802–815.

Zhuang, H.Y. & Chen, G.X. & Hu, Z.H. et al. 2016. Influence of soil liquefaction on the seismic response of a subway station in model tests. *Bulletin of Engineering Geology and the Environment* 75(3): 1169–1182.

Zhuang, H.Y. & Wang R. & Shi, P.X. et al. 2019. Seismic response and damage analysis of underground structures considering the effect of concrete diaphragm wall. *Soil Dynamics & Earthquake Engineering* 116: 278–288.