Failure modes analysis of a multi-story subway station under stochastic earthquake based on probability density evolution method

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Abstract

With the deep development and utilization of underground space, complex underground structures represented by multi-story subway station structure are constantly emerging. The damage of DAIKAI subway station during the 1995 Kobe earthquake indicates that underground structures may be seriously damaged under strong earthquake. Based on the probability density evolution method (PDEM), this paper studies the failure mode of a multi-story subway station structure under rare earthquake from the perspective of stochastic analysis, and gives the vulnerable spot of the multi-story subway station structure. It is found that the story drift of the four story of the structure does not exceed the elastic-plastic limit, but the failure probability of most structure components is more than 0.5. The vulnerable spots of the multi-story subway stations structure are mainly including the central columns, plates in middle stories, top plates, joints of bottom plate and sidewall. Failure of the internal components, such as central columns and plates in middle stories, are mainly bending failure, while failure of the outer frame components, such as the top and bottom plates and side walls, are mainly shear failure. In addition, the failure modes of multi-story subway stations can be roughly divided into four types. In the failure mode type I and II, most of failure appears at both vertical and horizontal components, while in the failure mode type III and IV most of failure occurs at horizontal components.

Keywords: **Multi-story subway station, Probability density evolution method, Stochastic earthquake motion, Vulnerable spot, Failure mode**

1 Introduction

With the deep development and utilization of underground space, complex underground structures represented by multi-story subway station structure are constantly emerging. During the 1995 Hanshin earthquake, the DAIKAI subway station was badly damaged [1][2], which led to the intensive research of seismic performance of subway station structures [3][4].

Compared with the typical single-story or two-story subway station, the structure of multi-story subway station structure is more complex, which causes the vulnerable spots and failure mode of the structure not easy to be undetected. However, up to now, most scholars have adopted deterministic methods, such as numerical dynamic time history analysis method [5][6] and model test method [7] under one or several given ground motions as well as Pushover analysis method [8][9], to explore the seismic responses and vulnerable spots of the structure without reasonable consideration of the randomness of the ground motion.

In order to fully understand the weak link of subway station structure under earthquake and based on the probability density evolution method (PDEM) and the thought of equivalent extreme event, the seismic reliability of a multi-story subway station structure under random earthquake is studied in this paper by using deformation and component strength as evaluation indexes. The main failure mode types of the multi-story subway stations structure under stochastic earthquake motion are summarized.

2 Project background

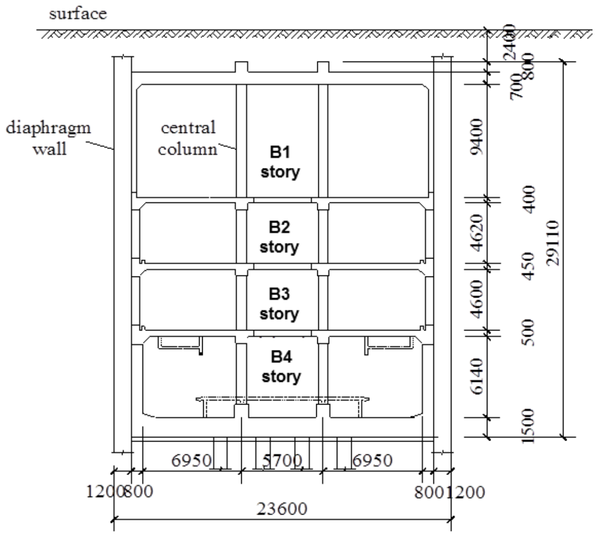

Figure 1. Standard cross section of the subway station, dimensions in mm

The multi-story subway station analyzed in this paper is a four-story three-span island station which located in Shanghai, China. Fig. 1 gives the standard cross section size of the station structure. The width and height of the standard section of the station is 23.6m and 29.1m, respectively, and the buried depth of the roof is 3.2m. The station is constructed by cut and cover method, and the diaphragm wall is used in the enclosure structure. The inner lining wall is connected to the diaphragm wall through the embedded parts, so that both of them bear forces together and form the side wall. The longitudinal distance between central columns is 8m. The cross section size of the column in B1 and B2 story is 1.1m long and 0.7m wide, and the size of the column in the B3 and B4 story is 1.4m and long 0.7m wide. According to "Chinese Code for Seismic Design of Urban Rail Transit Structures" [10], the shear wave velocity of the soil is 150m/s.

3 Numerical model

The dynamic analysis model of soil structure interaction (SSI) is established in the finite element code ABAQUS [11]. Mohr-Coulomb constitutive model with Rayleigh damping is applied to the soil. The Poisson's ratio of soil is 0.3, and the internal friction angle and cohesion are 15° and 20kPa, respectively.

Beam element (B21) is chosen for the structure. Central columns are made of C45 concrete [12], whose elastic modulus, tensile and compression strength are 33.5GPa, 2.51 and 29.6 MPa, respectively. Other parts of the structure were made of C35 concrete, whose parameters are 31.5GPa, 2.20 and 23.4 MPa, respectively. Poisson's ratio of both C35 and C45 concrete is 0.2. The concrete damaged plasticity model is adopted to better simulate the dynamic response of the structure. The calculation of damage parameters has been done in previous studies [8][9]. Idealized elastic-plastic model was selected for rebar. Rebar used in central columns and other parts were HRB400 and HRB335, respectively. And the yield strength of HRB400 and HRB335 is 400MPa and 335MPa, respectively. The soil-structure interaction is defined by the Coulomb friction law. The coefficient of friction is assumed to be 0.4, which is equivalent to the friction angle of 22˚.

The size of the structure is determined by the axis of the standard cross section shown in Fig. 1. In this paper, the single side width of the soil mass is 250m, which is more than 3 times the structural width specified in "Chinese Code for Seismic Design of Buildings" [13]. The depth of soil is 85m. The infinite element boundary is adopted as the lateral soil boundary to reduce the boundary effect [11]. The established numerical model is shown in Fig. 2.

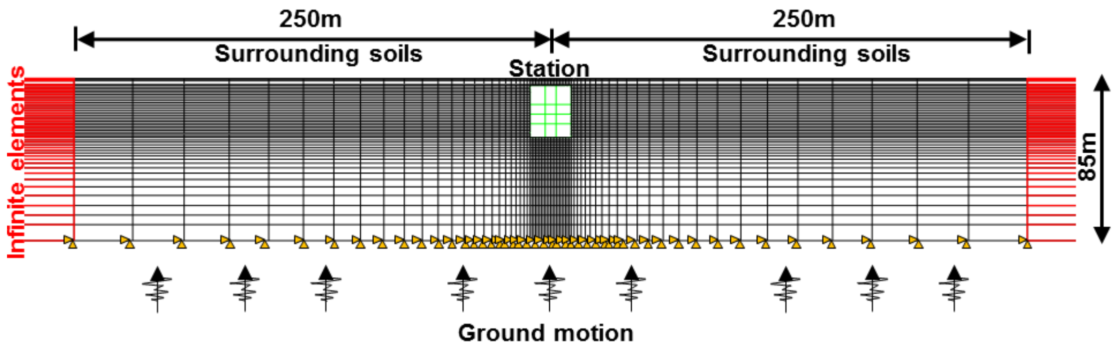

Figure 2. Numerical model of the underground subway station with surrounding soils

4 Process of PDEM

4.1 Numerical analysis process of PDEM

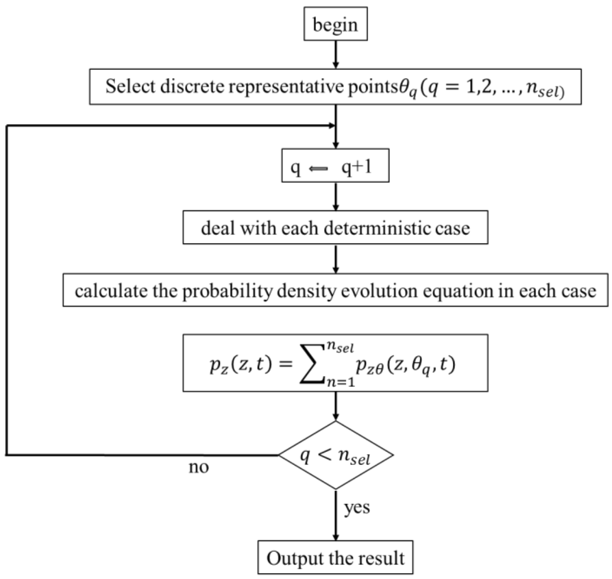

Figure 3. Basic steps of PDEM

The probability density evolution method is proposed by Li and Chen [14] based on the principle of probability conservation. After more than ten years of development, a relatively complete system of PDEM has been formed. The following is a brief introduction to the specific steps of probability density evolution analysis of structural random response. For more detailed contents of the method, please refer to the references [15].

The basic steps of stochastic response analysis of structures using PDEM are shown in Fig. 3, which are mainly divided into four steps. First are the discretization of probability space and the determination of the probability. Select a discrete set of representative points $\theta_q(q=1,2,\cdots,n_{sel})$ in the random parameter space Ω_Θ, where n_{sel} represents the total number of the points. At the same time, according to the principle of selecting points, the probability of each representative point is determined. In this paper, we mainly study the vulnerable spots and failure mode of the structure under stochastic earthquake motion, which means the randomness comes from the input earthquake motion. Thus, in this paper, n_{sel} represents the number of stochastic earthquake motion samples.

The second step is to solve the deterministic dynamic system. For every representative point θ_q, carry out deterministic analysis on the dynamical system and then get the partial derivative of the concerned physical quantity to time $\dot{\mathbf{Z}}(\theta_q,t)$ $(q=1,2,\cdots,n_{sel})$. The deterministic method used in this paper is the dynamic time history analysis method, that is, each stochastic earthquake motion sample is taken as input, the dynamic time history analysis of the structure is carried out to obtain the partial derivative of the concerned physical quantity to time, such as structural deformation and internal forces.

The third step is to solve the probability density evolution equation. The generalized probability density evolution equation can be expressed as Eq. (1).

$$\frac{\partial p_{Z\Theta}(z,\theta,t)}{\partial t}+\dot{\mathbf{Z}}(\theta,t)\frac{\partial p_{Z\Theta}(z,\theta,t)}{\partial z}=0 \tag{1}$$

For each selected representative point $\theta_q(q=1,2,\cdots,n_{sel})$, introduce $\dot{\mathbf{Z}}(\theta_q,t)$ into Eq. (1) and solve the equation under the corresponding initial conditions and boundary conditions using the finite difference method. Denote the solution as $p_{Z\Theta}(z,\theta_q,t)$. In this chapter, we use the finite difference method of Total Variation Diminishing (TVD) to solve the generalized probability density evolution equation.

The last step is to obtain the final solution through summation. Synthesize the solutions in previous step to obtain the numerical solution of PDEM equation, which is expressed as Eq. (2).

$$p_Z(z,t)=\sum_{q=1}^{n_{sel}} p_{Z\Theta}(z,\theta_q,t) \tag{2}$$

4.2 Generation of stochastic earthquake motions

In the numerical solution process of PDEM, the stochastic process of earthquake motion needs to be discrete in the probability space, and a certain number of stochastic earthquake motion samples are obtained. At present, among the various simulation methods of stochastic process, the spectral representation method, which is formally proposed by Shinozuka [16], has been improved after more than 40 years of development. However, in order to ensure the appropriate accuracy, this method often requires a lot of random variables and a large amount of computation. In this paper, Spectral representation - Random function method proposed by Liu et al. [17] is used to simulate the random process of ground motion. This method reduces the number of random variables to 1-2. 254 representative points are selected in the probability space of the basic random variable space Ω_{Θ}, and 254 earthquake motion samples are generated for the dynamic time history analysis of the numerical model. According to "Chinese Code for Seismic Design of Buildings" [13], the station site classification is IV and the seismic fortification intensity is 7 (PGA of rare earthquake equals to 0.22g). The relevant parameters for generating the ground motion samples are determined according to "Chinese Code for Seismic Design of Buildings" [13]. Fig. 4 gives 3 typical ground motion samples.

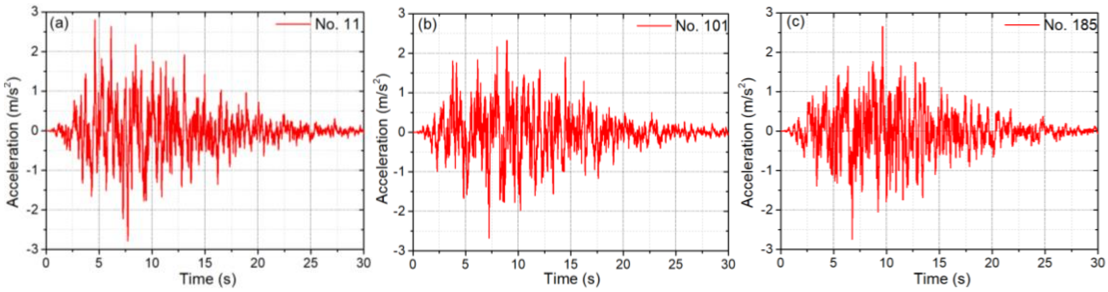

Figure 4. Typical acceleration time history samples

5 Result analysis

5.1 Structural reliability evaluation based on story drift

When evaluating the seismic performance of subway station structure, the maximum response value is often concerned. Therefore, based on PDEM and the equivalent extreme event thought, the corresponding equivalent extremum events are constructed from the deformation index to calculate the seismic reliability of the multi-story subway station structure under stochastic earthquake motion.

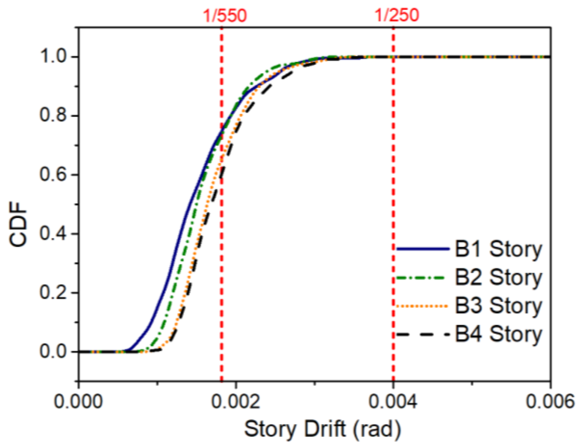

Figure 5. CDF of the extreme value of story drift

The story drift is an important index for evaluating the seismic performance of the structure from the point of view of deformation. Fig. 5 shows the cumulative probability distribution of story drift of four stories. "Chinese Code for Seismic Design of Buildings" [13] stipulates that the elastic limit of story drift of the underground structure is 1/550, and the elastoplastic limit of story drift is 1/250. The story drift less than 1/550 indicates that the structure has no damage or slight damage without repair; the story drift beyond the elastic limit means that the structural damage needs to be repaired, and the story drift over the elastoplastic limit means that the structural damage is serious. It can be obtained from Fig. 5 that the structure reliability of B1-B4 story is 0.739, 0.724, 0.641, 0.588, respectively, according to the elastic limit of story drift; and the reliability of the B1-B4 story is all 1 according to the elastoplastic limit. It can be seen that the reliability of the B1-B4 story decreases from top to bottom, indicating that the reliability of the structure decreases gradually along the soil depth. On the one hand, because of the load transfer, the axial pressure of the deep column increases obviously [18]; on the other hand, the depth increase makes the soil and water pressure of the deep side wall increase, which has a negative effect on the structure safety. In general, when the story drift is used as the deformation index to evaluate the structural reliability, the story drifts of four stories are less than the elastoplastic limit of story drift. This indicates that, the four stories of the structure are in two stages of slight damage and moderate damage, and there is no serious damage under the earthquake motion intensity of PGA=0.22g.

5.2 Failure probability analysis of structural components

The failure probability of structural components is calculated by strength index of components. According to the deterministic dynamic time history analysis, the internal force extremums of the component ends of the structure under 254 stochastic earthquake motions are obtained. Combined with the idea of equivalent extreme event, probability density evolution analysis is carried out, and the probability distribution of extreme value of internal force is obtained. The internal force bearing capacity (bending capacity and shear capacity) of the component can be used as a conservative limit of strength index, which is calculated according to "Chinese Code for Design of Concrete Structure" [12].

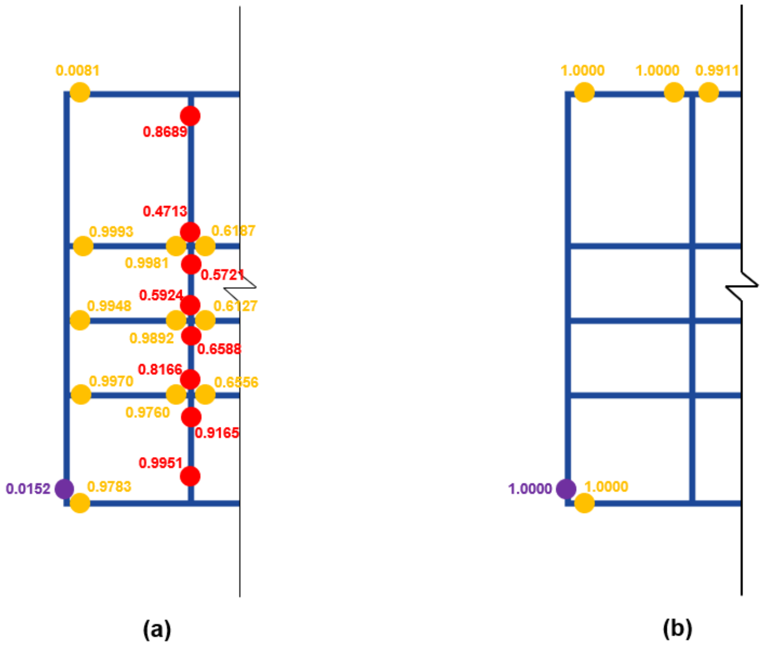

Figure 6. Failure probability of different positions (a) bending failure; (b) shear failure

Fig. 6 (a) (b) gives the failure probability of component ends according to the limit values of bending capacity and shear capacity. From Fig. 6 (a), it can be seen that the bending failure probability of the vast majority of internal components, including the columns and plates in middle stories, is all more than 0.5, which indicates that these internal components have great possibility of bending failure under the earthquake motion intensity of PGA=0.22g. However, the bending failure probability of outer frame components such as top and bottom plates, side walls is very close to 0 except for the joint of bottom plate and sidewall. This is because, in order to bear the peripheral water and soil pressure, the size and stiffness of outer frame components is obviously larger than the internal components of the structure, which makes the bending deformation of the end of the internal components increase, thus the bending moment may exceed the bending capacity. In addition, we can see from Fig. 6 (a) that the side span of plates in middle stories is the largest failure probability component, and the failure probability of the component ends is all more than 0.95. From Fig. 6 (b), it can be seen that the components whose shear failure probability greater than 0 are mainly the outer frame components, such as side walls, top and bottom plates, and the failure probability of the internal components is all equals to 0, which means that the shear failure will only occur in the outer frame. This is because the structure depth of the multi-story subway station is much larger than the ordinary subway station, the water and soil pressure on the outer frame is obviously increased, so the outer frame of the structure is more prone to shear failure. From the perspective of components failure probability, the vulnerable spots of the multi-story subway station structure are mainly the columns (especially in bottom story), plates in middle stories, top plates, and joints of bottom plate and side wall. In general, although it can be seen from Fig. 5 that the story drifts do not exceed than the elastoplastic limit, but most of the components of the structure may exceed the limit of bearing capacity. Therefore, the limit of the story drifts of underground structure in “Chinese Code for Seismic Design of Buildings” [13] may need further study.

5.3 Analysis of structural failure modes

Four types of failure modes can be obtained after sorting out the failure components according to the analysis of 254 stochastic earthquake motion cases. Fig. 7 shows the failure location of four types of failure modes, and Table 1 gives the number of cases corresponding to each failure mode type and failure components. In Fig. 7, red points indicate bending failure, blue points indicate shear failure, and purple points indicate bending shear failure.

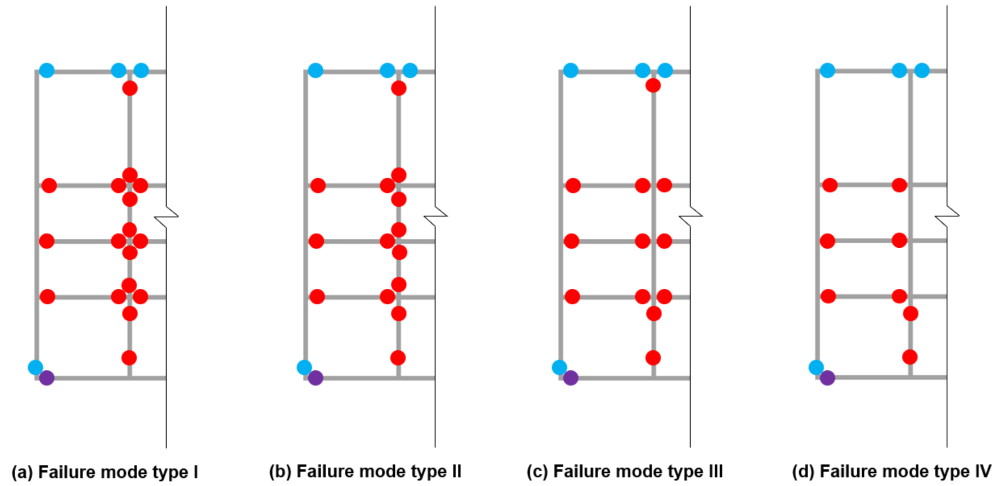

Figure 7. Classification of structural failure modes

From Table 1, we can see that the I-IV failure modes contain 123, 84, 37, and 10 cases, accounting for 48.4%, 33.1%, 14.6%, and 3.9% of the total cases respectively. In the four type of failure modes, type I has the largest number of failure components. As shown in Fig. 7 (a), bending failure occurs at almost all the end of columns and plates in middle stories, and shear failure and bending shear failure occur respectively at the end of the top plates and the joints of bottom plate and sidewall. From Fig. 7 (b), it can be seen that compared with failure mode type I, failure components in type II do not include middle span of the plates in middle stories. From Fig. 7 (c), it can be seen that compared with failure mode type I, failure components in type III do not include columns in the middle stories. Type IV is one of the four failure modes with the least failure components. As shown in Fig. 7 (d), the failure components in type IV mainly include the side span plates in middle story, top plates, joints of bottom plate and sidewall, central columns in bottom story. In general, in the failure mode type I and II, most of failure appears at both vertical and horizontal components, while in the failure mode type III and IV most of failure occurs at horizontal components. The number of failure components and the number of the corresponding cases all decrease from the type I to type IV, which indicates that the structure tends to appear failure of most components under the rare earthquake intensity of 7 seismic fortification intensity.

Table 1. Classification and description of failure modes

Failure mode types	Failure location description	Total cases
I	Plates in middle story; top plates; joints of bottom plate and sidewall; central columns in most stories	123
II	Side span plates in middle story; top plates; joints of bottom plate and sidewall; central columns in most stories	84
III	Plates in middle story; top plates; joints of bottom plate and sidewall; central columns in bottom story	37
IV	Side span plates in middle story; top plates; joints of bottom plate and sidewall; central columns in bottom story	10

6 Conclusions

Based on PDEM and finite element elastoplastic dynamic time history analysis, the seismic reliability of a multi-story subway station structure under stochastic earthquake motion is studied in the presented paper with the evaluation index of story drift and component strength. The vulnerable spots and main failure modes are analyzed and summarized. The main conclusions are as follows:

(1) Story drifts do not exceed than the elastoplastic limit, but most of the components of the structure may exceed the limit of bearing capacity, which means limit of the story drifts of underground structure in “Chinese Code for Seismic Design of Buildings” [13] may need further study.

(2) From the perspective of failure probability of structural components, the vulnerable spots of the multi-story subway station structure are mainly the columns (especially in bottom story), plates in middle stories, top plates, joints of bottom plate and sidewall.

(3) Failure of the internal components, such as central columns and plates in middle stories, are mainly bending failure, while failure of the outer frame components, such as the top and bottom plates and side walls, are mainly shear failure.

(4) The failure modes of the multi-story subway station structure can be roughly divided into four types. The number of failure components and the number of the corresponding cases all decrease from the type I to type IV. In the failure mode type I and II, most of failure appears

at both vertical and horizontal components, while in the failure mode type III and IV most of failure occurs at horizontal components.

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References

[1] Nakamura, S., Yoshida, N., and Iwatate, T. (1996) Damage to Daikai subway station during the 1995 Hyogoken-Nambu earthquake and its investigation, *Japan Society of Civil Engineers*, Committee of Earthquake Engineering, 287-295.

[2] Yamato, T., Umehara, T., Aoki, H., Nakamura, S., Ezaki, J., and Suetomi, I. Damage to Daikai subway station, Kobe rapid transit system and estimation of its reason, *Proceedings, technical conference on the great Hanshin-Awaji Earthquake*, JSCE, Tokyo, 1996, 247-254. (in Japanese)

[3] Chen, G., Wang, Z., Zuo, X., Du, X., and Gao, H. (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.

[4] Khani, S., and Homami, P. (2014) Seismic performance of underground shallow subway stations in soft soil, *Journal of Engineering Geology* **8**(1), 1983-2002.

[5] Parra-Montesinos, G. J., Bobet, A., and Ramirez, J. A. (2006) Evaluation of soil-structure interaction and structural collapse in Daikai subway station during Kobe earthquake, *ACI structural journal* **103**(1), 113.

[6] Zhuang, H., Hu, Z., Wang, X., and Chen, G. (2015) Seismic responses of a large underground structure in liquefied soils by FEM numerical modelling, *Bulletin of Earthquake Engineering* **13**(12), 3645-3668.

[7] Chen, G., Chen, S., Qi, C., Du, X., Wang, Z., and Chen, W. (2015) Shaking table tests on a three-arch type subway station structure in a liquefiable soil, *Bulletin of Earthquake Engineering* **13**(6), 1675-1701.

[8] Chen, Z. Y., Chen, W. and Zhang, W. (2014) Seismic performance evaluation of multi-story subway structure based on pushover analysis, *Advances in Soil Dynamics and Foundation Engineering* 444-454. ASCE.

[9] Chen, Z. Y., Chen, W., Zhang, W. and Lou, M. L. (2016) Effects of Axial Compression Ratio of Central Columns on Seismic Performance of a Multi-Story Underground Structure, *International Journal of Computational Methods* **13**(04), 1641014.

[10] GB50909 (2014) *Code for Seismic Design of Urban Rail Transit Structures*, China Planning Press, Beijing, China.

[11] ABAQUS, Users Manual V. 6.14. (2015) Dassault Systemes Simulia Corp., Providence, RI.

[12] GB50010 (2010) *Code for Design of Concrete Structure*, China Architecture & Building Press, Beijing, China.

[13] GB50011 (2010) *Code for Seismic Design of Buildings*, China Architecture & Building Press, Beijing, China.

[14] Li, J. and Chen, J. (2008) The principle of preservation of probability and the generalized density evolution equation, *Structural Safety* **30**(1), 65-77.

[15] Li, J. and Chen, J. (2009) *Stochastic dynamics of structures*, John Wiley & Sons.

[16] Shinozuka, M. (1972) Monte Carlo solution of structural dynamics, *Computers & Structures* **2**(5-6), 855-874.

[17] Liu Z.J., Zeng B. and Wu L.Q. (2015) Simulation of non-stationary ground motion by spectral representation and random functions, *Journal of Vibration Engineering* **28**(3), 411-417. (in Chinese)

[18] Chen, Z., Chen, W., Li, Y. and Yuan, Y. (2016) Shaking table test of a multi-story subway station under pulse-like ground motions, *Soil Dynamics and Earthquake Engineering* **82**, 111-122.