HYBRID SIMULATION OF SUBWAY STATION STRUCTURE SUBJECTED TO EARTHQUAKE GROUND MOTION

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Abstract

Earthquake is one of the largest natural hazards which cause numerous life lost and infrastructure damage throughout the history of mankind. As an essential component of underground transportation system, subway station is designed to provide nonstop-function after both frequent and rare seismic events. Though it is generally believed that the seismic performance of underground structures is superior to superstructure since underground structures are surrounded and restricted by soil and rock, several severe damages of underground structure have been reported after recent huge earthquake attacks, especially the Daikai subway station during the Hyogoken-Nanbu earthquake in 1995.

Hybrid simulation method, an innovative dynamic testing method originating from pseudo-dynamic testing method and substructure analysis technique while reinforced by modern numerical integration algorithm and advanced hardware control capacity, is believed to be a promising seismic testing solution with better effect but lower cost compared with conventional seismic testing methods.

The research work of applying hybrid simulation method on studying dynamic performance of subway station structure subjected to earthquake loading was presented in this paper. A typical rectangular subway station was studied in this application. An intermediate column (truncated at middle as inflection point) in the subway station was adopted as physical sub-structure, while the remainder of the subway station and the soil surrounding it was simulated in OpenSees as numerical sub-structure. The dimensions of the soil domain modeled in this case were 200 m long and 70 m deep. The rectangular subway station section was 17 m × 7.2 m, which was embedded 4.8m deep below ground surface. A novel steel specimen was used for the physical loading. The bending stiffness of steel column specimen could be changed by replacing the screws at the column foot; therefore, the bending stiffness could be specified according to the real intermediate column in the subway station and the experimental specimen could be easily reconstructed by just replacing screws after encountering unrecoverable damage. The horizontal displacements and shearing forces at the middle of intermediate column subjected to different earthquake ground motions were provided in this paper. The feasibility and accuracy of the proposed hybrid simulation testing method was further discussed when comparing the hybrid simulation results with the ones from pure numerical analysis.

Keywords: hybrid simulation; OpenSEES; steel specimen; subway station

1. Introduction

In 1995, Daikai subway station suffered a severe damage during the Hyogoken-Nanbu earthquake. The Daikai station was built by cut and cover method (1962-1964), about 15 km away from the epicenter. During the earthquake, more than 30 central columns were completely destroyed, which directly led to the destruction of Daikai station. In the original design of Daikai station, seismic load was not considered. The design was very conservative and the safety margin is sufficient enough in static condition. There was no liquefied soil layers around the station and the station was not in the fault area, but it was unexpectedly damaged in such a severe earthquake.

Research on the seismic performance of Daikai station were conducted with both numerical and experimental methods [1]. In the respect of numerical modelling, stratum structure analysis method is widely used. Non-linear behavior of soil material, non-linear soil-structure interaction could be considered in such method [2]. Analytical or semi-analytical methods, such as finite element methods, boundary element methods, and infinite element elements, are widely used in the solving process. To be specific, finite element methods is the most flexible and convenient. Huo used the commercial program ABAQUS to conduct stratum structure analysis and gave an explanation of the failure mechanism of the Daikai station [3]. Zhuang developed a dynamic nonlinear soil model to describe the characteristics of soils under cyclic loadings and shed some light on the damage process of Dakai station [4].

In the respect of experimental research, scaled tests of subway station have been conducted to illustrate damage process of subway stations. Scaled test is one of the important means to understand the mechanism of earthquake damage to underground structures. The damage patterns of underground structures would be reproduced in the test. The test results would be important references to calibrate the accuracy of the numerical modelling [5,6]. The traditional shaking table test of subway station is performed under the gravity acceleration environment of 1g. However, the stress level of the model soil caused by the self-weight is reduced as the scale ratio. Therefore, in the regard of mechanical properties of soil, there will be an obvious difference between the model soil and prototype soil. Nonetheless, through the reasonable design of the test procedure, qualitative analysis could be achieved with the traditional shake table method, quantitative results cannot be easily obtained.

Hybrid simulation should be a supplement to the seismic test of subway stations. However, hybrid simulation technique has not been fully applied in the study of seismic performance of subway station. Hybrid simulation technique could take advantages of both numerical modelling and experimental research [7-9]. In this paper, a specimen with specified lateral stiffness is developed for the hybrid simulation. The central column could be regarded as physical sub-structure while the rest of the model are regarded as numerical sub-structure. Three cases of different seismic waves were conducted to illustrate the accuracy of hybrid simulation.

2. Steel specimen design

The hybrid simulation technique has not been applied in the underground structures. Convergence may not always be obtained in hybrid simulation in the numerical part. Therefore, unlike quasi-static test or shaking table test, due to physical system and communication delays, sensor noise, joint friction, and other experimental errors, hybrid dynamic simulations can lose accuracy or even go unstable during the test process. A reusable specimen should be developed to fulfill the hybrid simulation of underground structures. Therefore, the steel column specimen was designed to meet the requirements mentioned above.

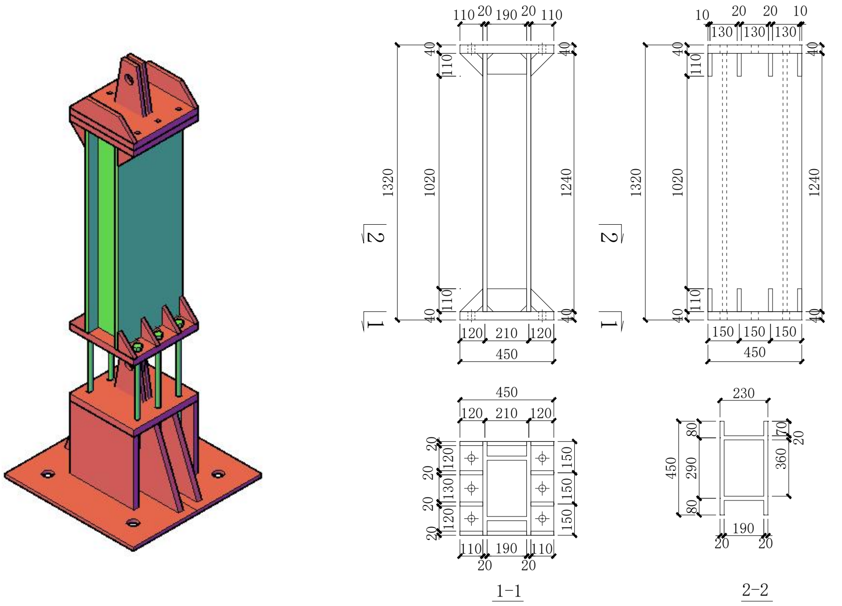

Fig. 1 Design drawing of specimen

As shown in Fig.1, the lateral stiffness of steel specimen could be determined by changing bottom screws. Therefore, lateral stiffness could be specified to meet the requirement of the prototype structure. The lateral stiffness of the box-shape steel specimen is much larger than that of the bottom part. It could be predicted that the failure would be concentrated on the screws. Previous static test results show that buckling would happen in screws. Based on Eqs.(1)-(4), physical sub-structure with different lateral stiffnesses could be obtained to meet the test requirements.

$$\delta=\frac{l_1^3}{3E_1I_1}+\frac{l_1^2}{k_m} \tag{1}$$

$$I_1=\frac{b_1h_1^3}{12}-\frac{b_2h_2^3}{12} \tag{2}$$

$$k_m=\frac{M}{\varphi}=\frac{n\pi d^2a^2E_2}{8l_2} \tag{3}$$

$$K=\frac{1}{\delta}=\frac{3E_1E_2I_1n\pi d^2a^2}{n\pi d^2a^2E_2l_1^3+24E_1I_1l_1^2l_2} \tag{4}$$

Where, K is the lateral stiffness of the steel specimen, l_1 s the height of the box-shaped column, E_1 is the elastic modulus, I_1 is the inertia moment of the box-shaped column, k_m is the rotation stiffness of the support, b_1 is the width of the outer surface of the box-shaped column, h_1 is the height of the outer surface of the box-shaped column, b_2 is the width of the inner surface of the box-shaped column, h_2 is the height of the inner surface of the box-shaped column, n is the number of single-sided screws, d is the diameter of the screws, and a is the distance between the screws.

3. Hybrid simulation process

OpenSEES was used for the numerical part of hybrid simulation [10]. The soil layers and parameters in the analysis area are utilized for modeling, as listed in Table 1. The soil layers are regarded as the homogeneous site. Therefore, the weighted mean of wave velocity is 250m/s while the weighted mean of unit weight is 1840 kg/m^3. An appropriate artificial boundary should be introduced to model the propagation process of seismic wave in the site. As shown in Fig.2, equal displacement boundary was introduced on the lateral sides while bottom of FEA model was fixed [11,12]. The dimension of soil domain is taken as 200m × 70m, The site model is taken long enough to neglect the effect of reflection on the lateral sides.

Table 1- Soil properties

No.	Soil layer	Depth (m)	Thickness (m)	Wave velocity (m/s)	Unit weight (kg/m^3)
1	fill	1.7	1.7	137	1730
2	silty clay	3.2	1.5	138	1830
3	sandy silt	6	2.8	140	1850
4	silty clay	9.6	3.6	126	1740
5	silty clay	13.3	3.7	133	1740
6	silty clay	17	3.7	141	1740
7	clay	21.6	4.6	153	1740
8	clay	26.3	4.7	187	1740
9	clay	31	4.7	203	1740
10	clay	35.3	4.3	230	1760
11	clay	39.6	4.3	254	1760
12	clay	43.9	4.3	281	1760
13	clay	48.3	4.4	297	1760
14	silt	52.7	4.4	339	1840
15	silt	57.1	4.4	387	1840
16	silt	61.6	4.5	362	1840
17	silt	66.1	4.5	357	1840
18	silt	70.0	5.4	365	1920

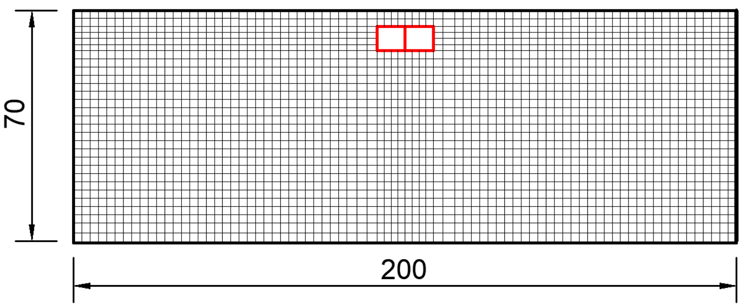

Fig 2. Cross section of FEM model (unit: m).

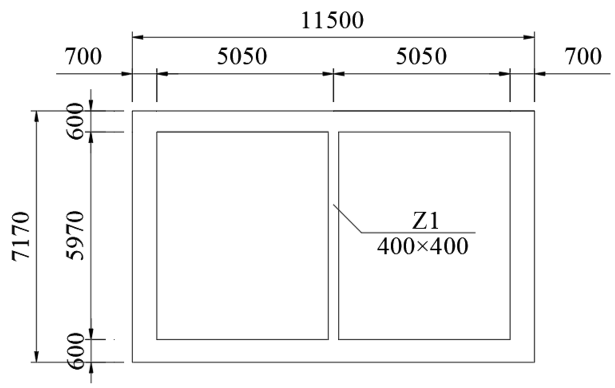

Fig 3. Cross section of station (unit: mm).

Fig.3 shows the dimensions of the typical station. The typical subway station section is 17m×7.2m, the station was embedded 4.8m deep below ground surface. The concrete compressive strength is 34.5 MPa whilst the corresponding strain is 0.002. The concrete crushing strength is 8.0 MPa whilst the corresponding strain is 0.004. Displacement-based beam-column elements are selected to simulate the roofs, floors, lateral walls, and central columns.

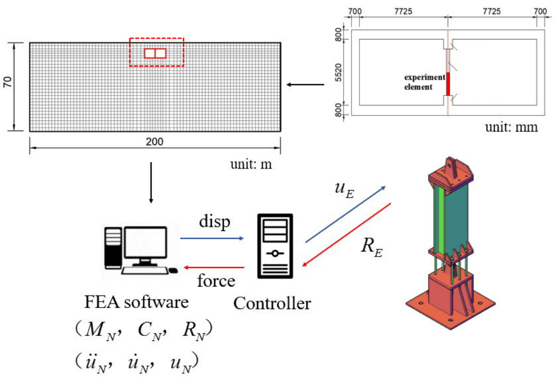

Fig 4. Cross section of FEM model (unit: m).

As shown in Fig.4, OpenFresco builds the bridge between the numerical sub-structure and physical sub-structure [13]. The half bottom central column was selected as the physical sub-structure while the rest of the FEA model was selected as the numerical sub-structure. Therefore, the substructure hybrid simulation technique was applied. Hybrid test method could be performed at full scale.

In the prototype structure, the central column is a RC specimen. Before the hybrid simulation process, a simple simulation was conducted to get the lateral stiffness. Equivalent stiffness principle is applied to determine the physical sub-structure, namely the steel specimen mentioned above. Based on Eqs.(1)-(4), the bottom screws could be determined.

4. Results and discussion

A series of hybrid simulation of the typical subway station were conducted with the steel specimen under the following cases: Shang Hai artificial wave, El Centro wave and Kobe wave. It should be noted that the peak acceleration of three waves is 0.12g.

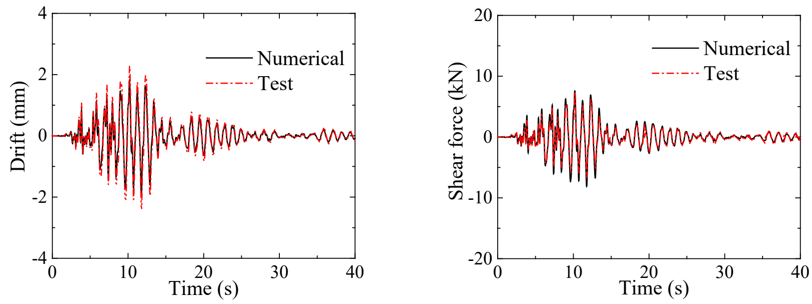

Fig. 5 Results of Kobe case

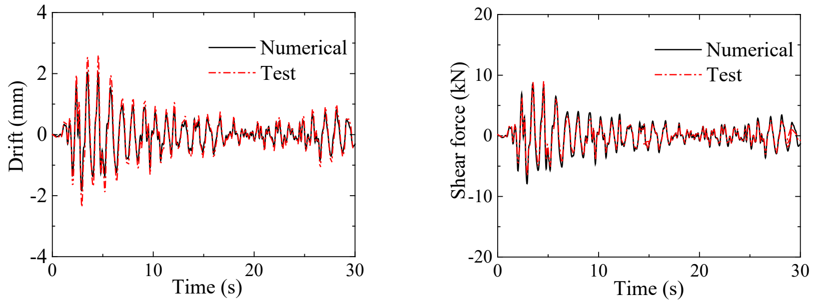

Fig. 6 Results of EI case

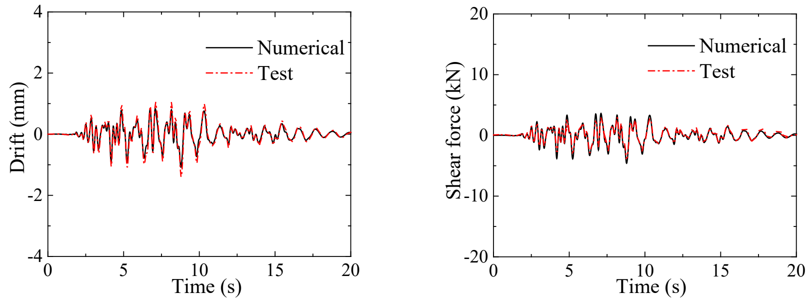

Fig. 7 Results of Shanghai case

The test results of three cases show a good agreement with the numerical results in Fig.5, Fig.6, and Fig.7. In the analysis of the seismic performance of typical subway station, the proposed hybrid simulation system composed by OpenSees, OpenFresco and MTS performs well. Moreover, the designed steel column specimen is capable of representing the central column in the prototype structure.

The equivalent stiffness principle is applied to determine the physical sub-structure. However, the plastic behavior of steel specimen and RC specimen is usually different. Although the hybrid simulation technique with the steel column specimen could be applied to reflect the seismic behavior of the typical subway station, it should be emphasized that such technique is only fit in the elastic stage of central column.

5. Acknowledgements

Yang proposed the main structure of this research and concluded the proposed models in this research. Cai conducted the experiment and analysis. All authors read and approved the final manuscript.

6. References

[1] Pitilakis K , Tsinidis G . Performance and Seismic Design of Underground Structures[M]// *Earthquake Geotechnical Engineering Design.* Springer International Publishing, 2013.

[2] PARRA M G J, BOBET A, RAMIREZ J A. Evaluation of soil-structure interaction and structural collapse in Daikai subway station during Kobe earthquake[J]. *ACI Structural Journal*, 2006, 103(1): 113–122.

[3] HUO H, BOBET A, FERNÁNDEZ G, et al. Load transfer mechanisms between underground structure and surround ground: Evaluation of the failure of the Daikai station[J]. *Journal of Geotechnical and Geoenvironmental Engineering,* 2005, 131(12): 1522–1533.

[4] Zhuang, H.Y., Cheng, S.G., Chen, G.X., 2008. Numerical simulation and analysis of earthquake damages of Dakai metro station caused by Kobe earthquake. *Rock Soil Mech.* 29 (1), 245–250.

[5] Chen Z Y, Liu Z Q. Effects of pulse-like earthquake motions on a typical subway station structure obtained in shaking-table tests[J]. *Engineering Structures,* 2019, 198: 109557.

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

[7] Mccrum D P , Williams M S . An overview of seismic hybrid testing of engineering structures[J]. *Engineering Structures,* 2016, 118:240-261.

[8] Mccrum D P , Broderick B M . Evaluation of a substructured soft-real time hybrid test for performing seismic analysis of complex structural systems[J]. *Computers & Structures,* 2013, 129:111-119.

[9] C.Yang, X.Cai*, Y. Yuan. Hybrid simulation of soil station system response to two-dimensional earthquake excitation. *Sustainability*, 2019,11(9), 2582

[10] McKenna F, Fenves G.L. 2001. The OpenSees command language manual, version 1.2, http://opensees.berkeley.edu, Pacific Earthquake Engineering Research Center, University of California, Berkeley.

[11] Bao X, Xia Z, Ye G. Numerical analysis on the seismic behavior of a large metro subway tunnel in liquefiable ground[J]. *Tunnelling & Underground Space Technology,* 2017, 66:91-106.

[12] Amorosi A, Boldini D, Elia G. Parametric study on seismic ground response by finite element modelling[J]. *Computers & Geotechnics,* 2010, 37(4):515-528.

[13] Schellenberg A, Kim H K, Takahashi Y. *OpenFresco Command Language Manual*[J]. 2009

