A comparison between large-size shaking table test and numerical simulation results of subway station structure

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ABSTRACT :

Based on the large-size shaking table test results of subway station structure built in liquefiable site, considering the influence of soil-structure nonlinear dynamic interaction by 2D finite element methods, the seismic response of soil-subway station structure system under different test conditions are analyzed by using ABAQUS software. In the analysis model, dynamic visco-plastic memorial nested yield surface model is used to model dynamic characteristics of site soils, and plastic-damage model is used to model dynamic characteristics of concrete of subway station structure. And then, the numerical simulation results and the shaking table test records are compared in detail in this paper. The results show that the numerical simulation results of seismic response of soil-subway station structure system are basically identical with those of the shaking table test records. So that, the analysis results and the shaking table test results are proved to be correct.

KEYWORDS: subway station structure; dynamic interaction of soil-subway station structure; seismic response; large-size shaking table test; numerical simulation

1. INTRODUCTION

With the development of social economy and the increasing of urban population, the traffic condition can't satisfy the demand of the existing passenger transport, so developing underground traffic is very imperative. The underground structures, being confined by the surrounding rock or soil, have long been assumed to have good anti-seismic ability. However, according to earthquake disaster in recent years, the underground structures are not always safe. Therefore, it is necessary to study on seismic behavior of underground structure.

In the research of the seismic response of underground structures in recent years, Liu Jinbo(2005) analyzed the seismic response of subway tunnels shielded with a stiff liner as a function of factors such as the distance between the twins tunnels, the elastic modulus and thickness of the lining by the complex response method. Taking ABAQUS as simulation platform and considering the interaction between vertical and horizontal seismic. Yang Linde(2003) designed the model box and conducted shaking table model test on subway station. Then, the numerical simulation of model test is performed based on the Lagrangian difference algorithm.

Due to lack of measured data for seismic response of soil-underground structure system, the numerical simulation is the chief treatment method, and the test research is relatively less, but the comparison between numerical simulation results and model test records is much less. By the comparative research between numerical simulation results and model test records, it verified the reasonableness of calculation model and the reliability of test results.

In this paper, taking ABAQUS software as simulation platform and considering soil-subway station structure dynamic interaction, the numerical simulation of subway station structure is conducted. And then, the numerical simulation results are compared with the test results.

2. BRIEF INTRODUCTION OF LARGE-SIZE SHAKING TABLE MODEL TEST OF LIQUEFIABLE SOIL-SUBWAY STATION STRUCTURE

The test is conducted on the large-size shaking table(6m×6m, 80t) in China Construction Science Research Institute. In the test, Nanjing fine sand is used as model soils, and the clay is placed on the top and bottom of the model box. The thickness of clay, sand and clay layers in model ground is respectively 0.24m, 1.2m and 0.16m from top to bottom of the model box, and the width of model ground is 4.1m. The thickness of overlaying soils above subway station structure is 0.08m. In order to decrease the effect of rigid boundary to structural dynamic response, two polystyrene foam boards placed beside two sidewalls of model box respectively. Before the test, the physical characteristics of model soil and micro-concrete are given by laboratory experiment. The schematic section of subway station structure and arrangement of accelerometers are showed as Figure.1. The acceleration response of model soil and strain response of model structure are recorded under different conditions. The basic laws of seismic response of station structure in liquefiable soils are recognized. The test records also provided some data for perfecting the analysis methodes of seismic response of subway station structure.

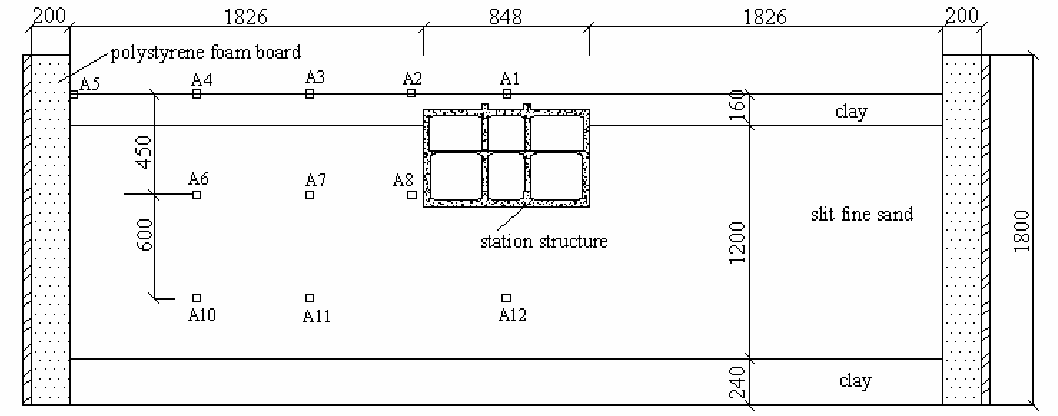


Fig.1 Schematic section of subway station structure and site model, arrangement of accelerometers (unit: mm)

3. ANALYSIS METHOD OF SEISMIC RESPONSE OF LIQUEFIABLE SOIL-SUBWAY STATION STRUCTURE

The soil-subway station structure system is considered as a plane strain problem. The columns of station structure are equivalent to a vertical wall by stiffness reduction method. The calculation region is the scope of model box. The shaking table test is used to be simulated the seismic response of subway station structure under horizontal ground motion, therefore, the vertical fixed and horizontal free hinge bearings are used for the bottom and lateral boundaries in numerical analysis. The grids gradually become bigger from near station structure to the artificial boundary, the meshes of soil-subway station structure system in two dimensional finite element analysis are showed as Figure.2. The model soils and station structure are simulated by four-node plane strain elements. In order to improve calculation speed, reduced integral elements are used to simulate model soils, and complete integral elements are used to simulated model structure. The contact face pairs are used to simulate dynamic transfer property of soil and station structure.

Dynamic visco-plastic memorial nested yield surface model is used to simulate the dynamic characteristics of soils. The density of soils is measured by laboratory experiment. The average velocity of shear wave of model soils is measured by SUMIT shallow seismograph. The physical and mechanical parameters of model soils are listed in Table.1. The subway station structure is of micro-concrete. Plastic-damage model is used to simulate dynamic characteristics of subway station structure concrete. According to similarity law, the model parameters are determinate, and they are listed in Table.2. Crushable foam model is used to simulate the characteristics of foam board. The parameters are listed as follows: the elastic modulus 4.13MPa, the poisson’s ratio 0.07, the density 15kg/m^3.

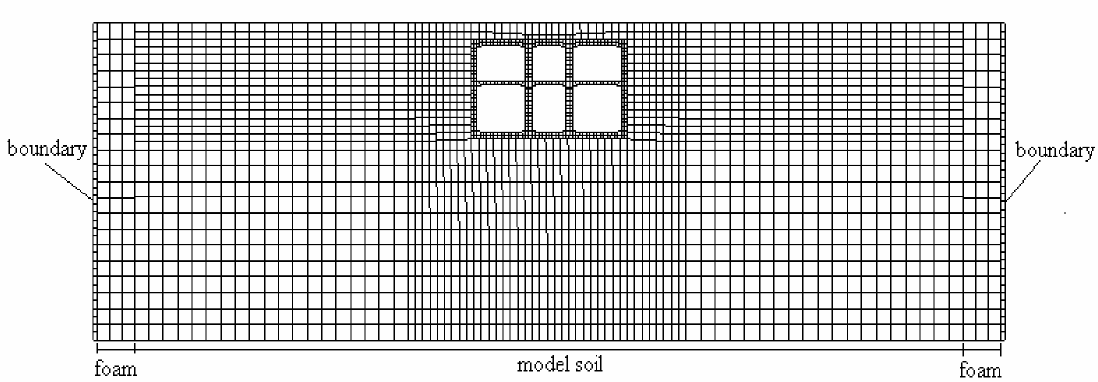


Fig.2 Meshes of soil- subway station structure system in two dimensional finite element analysis

Table.1 Physical and mechanical parameters of model soils

Soil layer	Thickness (m)	Density (g/cm^3)	Velocity of shear wave (m/s)	Poisson's ratio	Friction angle (°)
Clay	0.16	1.75	40	0.49	15
Slit fine sand	0.24	1.80	40	0.49	20
Slit fine sand	0.24	1.80	50	0.49	20
Slit fine sand	0.24	1.80	60	0.49	20
Slit fine sand	0.24	1.80	80	0.49	20
Slit fine sand	0.24	1.80	100	0.49	20
Clay	0.24	1.85	120	0.49	17

3. COMPARISON BETWEEN NUMERICAL SIMULATION RESULTS AND SHAKING TABLE TEST RECORDS

3.1.Acceleration response

The test records and numerical simulation results of accelerometers A1, A3, A6, A7, A10 and A12 are compared under C-K2 and C-E2 test condition, and the acceleration time-history and Fourier spectra are showed as Figure.3 and Figure.4. The second letter K, E, N respectively denote the action of Kobe wave, El-Centro wave, Nanjing artificial wave, the number 1, 2, 3 denote the load levels. The accelerometers A1 and A3 are placed in the upper soils. Because the upper layer is soft soils, the relative sliding between accelerometers and soils is occurred during test. Also, the vibrating pore water pressure of soils is high in shallow layer, and the dynamic constitutive model couldn't well simulate the nonlinear dynamic characteristics. Therefore, there is some difference between the numerical simulation results and the test records.

Table.2 Dynamic Plastic-damage model parameters of microconcrete for subway station structure

Model parameters	Parameter values
Elastic modulus E (MPa)	0.85×10^4
Poisson's ratio ν	0.18
Density ρ (kg/m^3)	2500
Expansion angle ψ (°)	32.4
Initial yield compressive stress σ_{c0} (MPa)	3.91
Ultimate compressive stress σ_{cu} (MPa)	5.69
Initial yield tensile stress σ_{t0}(MPa)	0.68
ω_t	0
ω_c	1
d_c	0
ξ	0.1

The accelerometers A6, A7, A10 and A12 are placed in the deeper soils,the waveform, the amplitude and characteristic of Fourier spectrum of acceleration time-history between test records and numerical simulation results are basically consistent. It indicated that the numerical simulation method could well simulate the seismic response of subway station structure in liquefiable soil. The peak acceleration of test records under different load conditions is listed in Table.3. In general, the numerical simulation results are in accordance with the test records under Kobe wave and Nanjing artificial wave, and the similarity of numerical simulation results and the test records is a little weaker under El-Centro wave.

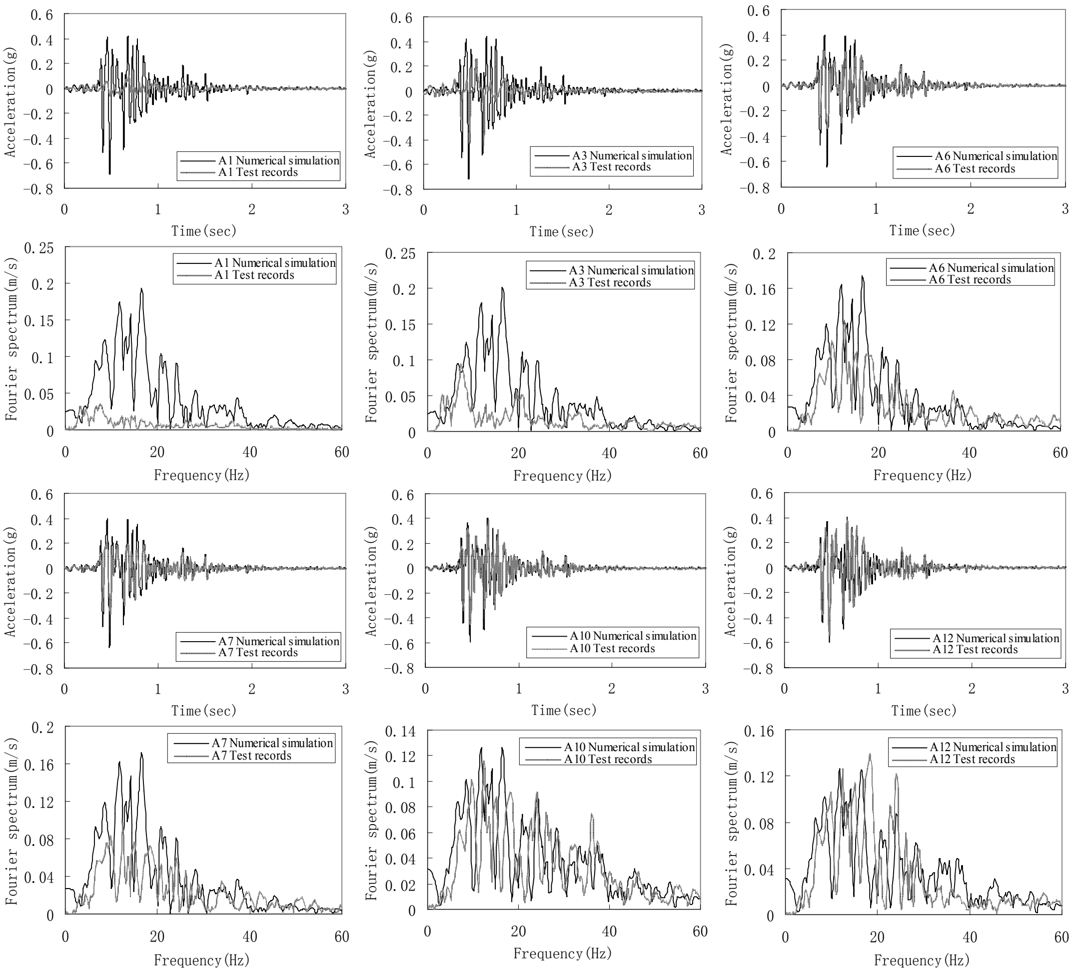


Fig.3 Acceleration time-history and Fourier spectra in different depth of model site under C-K2 test condition

Table.3 Peak acceleration at test points under load condition C-K2、C-N2 and C-E2 (unit:g)

Accelerometer	C-K2		C-E2		C-N2	
	Simulation	Test	Simulation	Test	Simulation	Test
A1	0.69	0.11	0.74	0.16	0.39	0.18
A2	0.70	0.10	0.75	0.16	0.37	0.20
A3	0.72	0.45	0.78	0.33	0.39	0.51
A4	0.74	0.23	0.82	0.35	0.40	0.36
A5	0.79	0.62	0.91	0.35	0.45	0.26
A6	0.64	0.34	0.69	0.32	0.33	0.27
A7	0.68	0.37	0.63	0.27	0.33	0.19
A8	0.63	0.13	0.67	0.16	0.33	0.19
A10	0.60	0.44	0.70	0.39	0.51	0.38
A11	0.59	0.54	0.70	0.50	0.51	0.33
A12	0.60	0.54	0.70	0.55	0.51	0.32

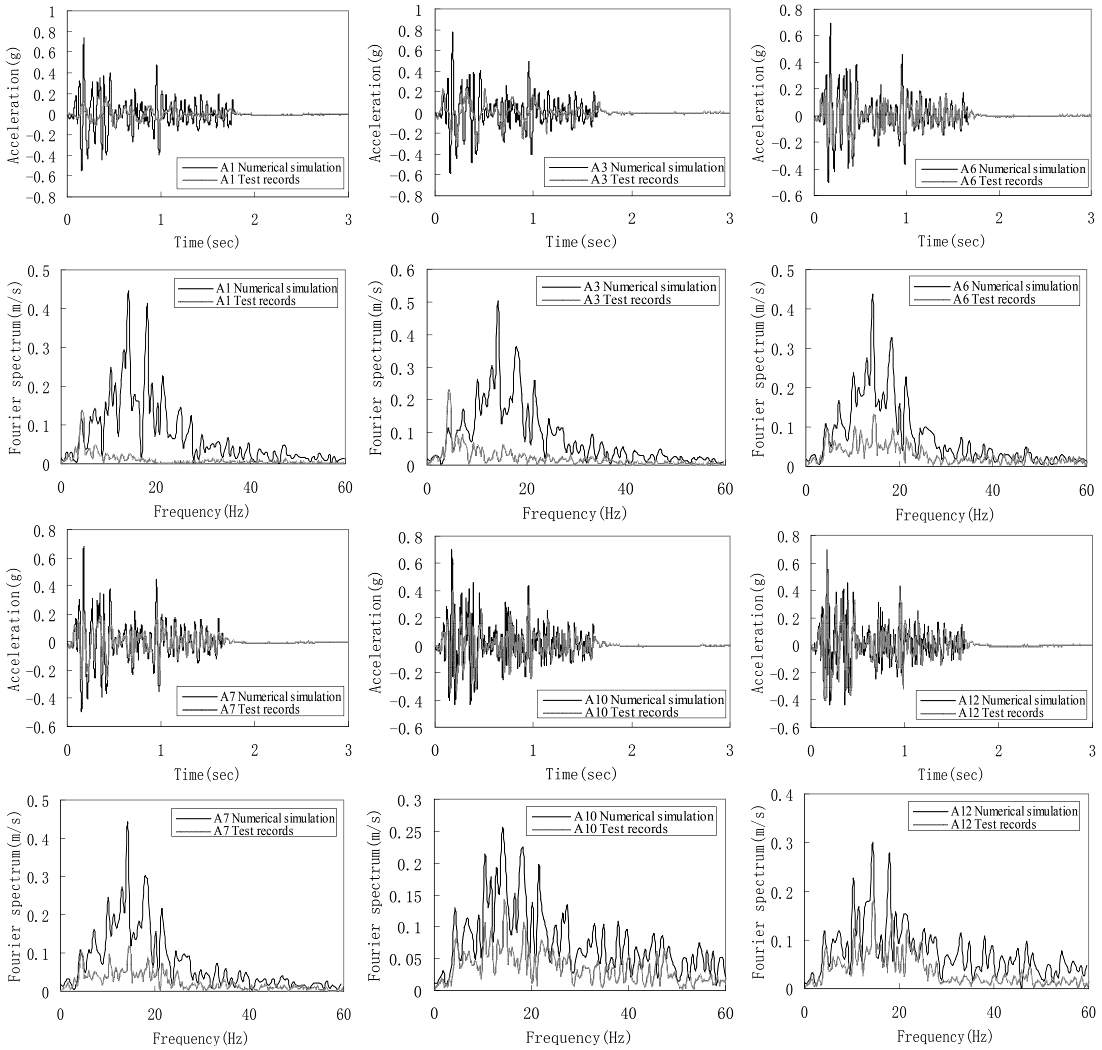


Fig.4 Acceleration time-history and Fourier spectra in different depth of model site under C-E2 test condition

The test records and numerical simulation results of accelerometers A1, A3, A6, A7, A10 and A12 are compared under test condition C-K1 and C-K3, and the acceleration time-history and Fourier spectra are showed as Figure.5 and Figure.6. The peak acceleration of test records under test conditions C-K1, C-K2 and C-K3 is listed in Table.4. The results have showed that the difference between the numerical simulation results and shaking table test records is increasing with the peak acceleration increasing of inputting seismic waves. The effect of simulation results under test condition C-K1 is best, and the effect of simulation results under test condition C-K2 is worse than that under test condition C-K1. But under the test condition C-K3, the difference between simulation results and test records is great. This is because that the subway station structure is floating, and the interface between soil and structure is separating under test condition C-K3. In the modeling, the contact face pairs are used to simulated dynamic transfer property of soil and station, and there is difference between the simulation and test. So that, the simulation of interface is need to be further researched.

3.2.Strain response

There are 53 strain gauges on the different cross sections. The strain gauges are kept the model structure in saturated soil for a long time,therefore, only 21 strain gauges could normal work, and the others are damage for wetting. The distribution situation of strain gauges is showed as Figure.7.

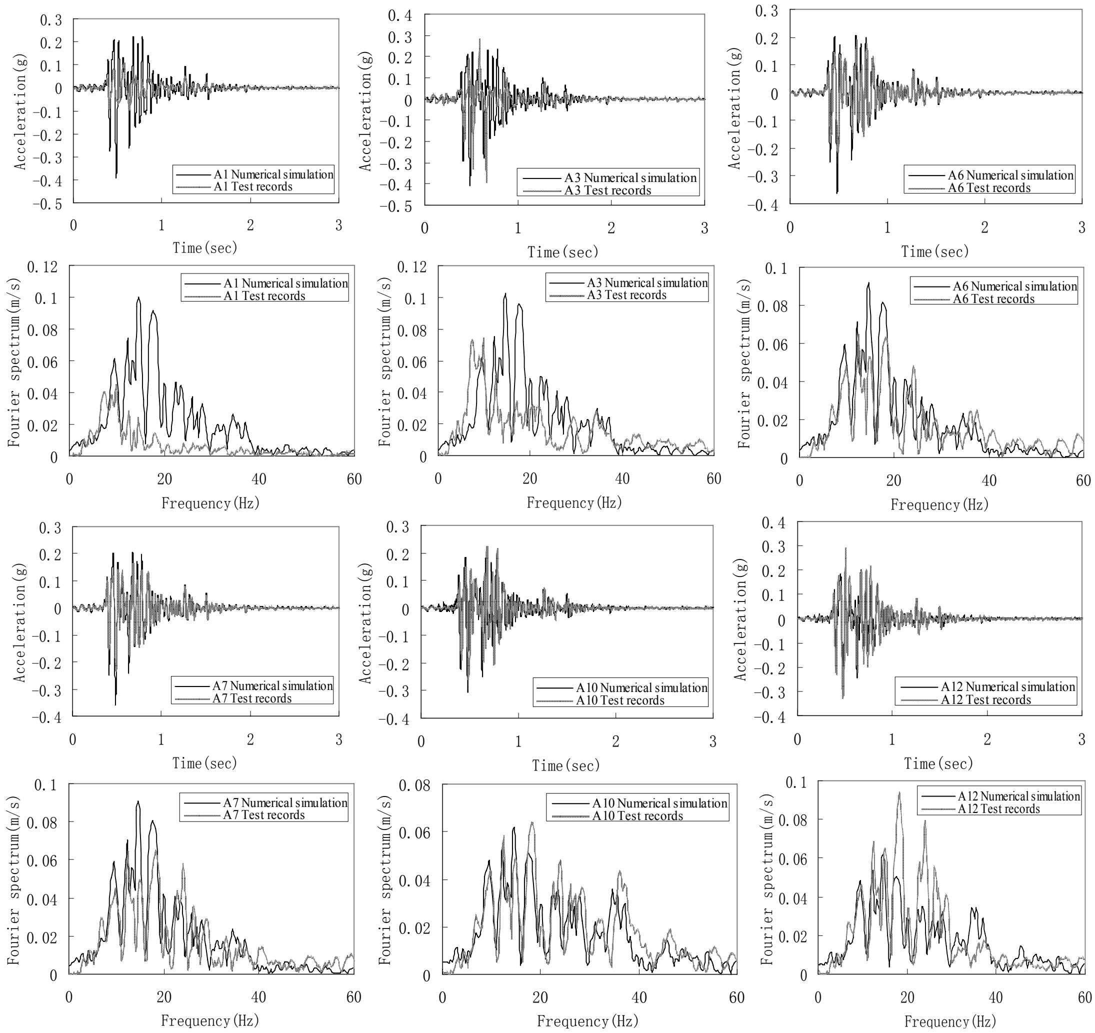


Fig.5 Acceleration time-history and Fourier spectra in different depth of model site unde C-K1 test condition

Table.4 Peak acceleration at test points under load conditions C-K1、C-K2 and C-K3 (unit:g)

Accelerometer	C-K1		C-K2		C-K3	
	Simulation	Test	Simulation	Test	Simulation	Test
A1	0.39	0.21	0.69	0.11	0.99	0.10
A2	0.40	0.23	0.70	0.10	1.00	0.13
A3	0.41	0.39	0.72	0.45	1.03	0.48
A4	0.42	0.30	0.74	0.23	1.06	0.27
A5	0.44	0.26	0.79	0.62	1.14	0.56
A6	0.36	0.21	0.64	0.34	0.92	0.54
A7	0.36	0.23	0.68	0.37	0.92	0.48
A8	0.35	0.13	0.63	0.13	0.91	0.11
A10	0.31	0.26	0.60	0.44	0.92	0.59
A11	0.31	0.29	0.59	0.54	0.92	0.53
A12	0.31	0.33	0.60	0.54	0.92	0.80

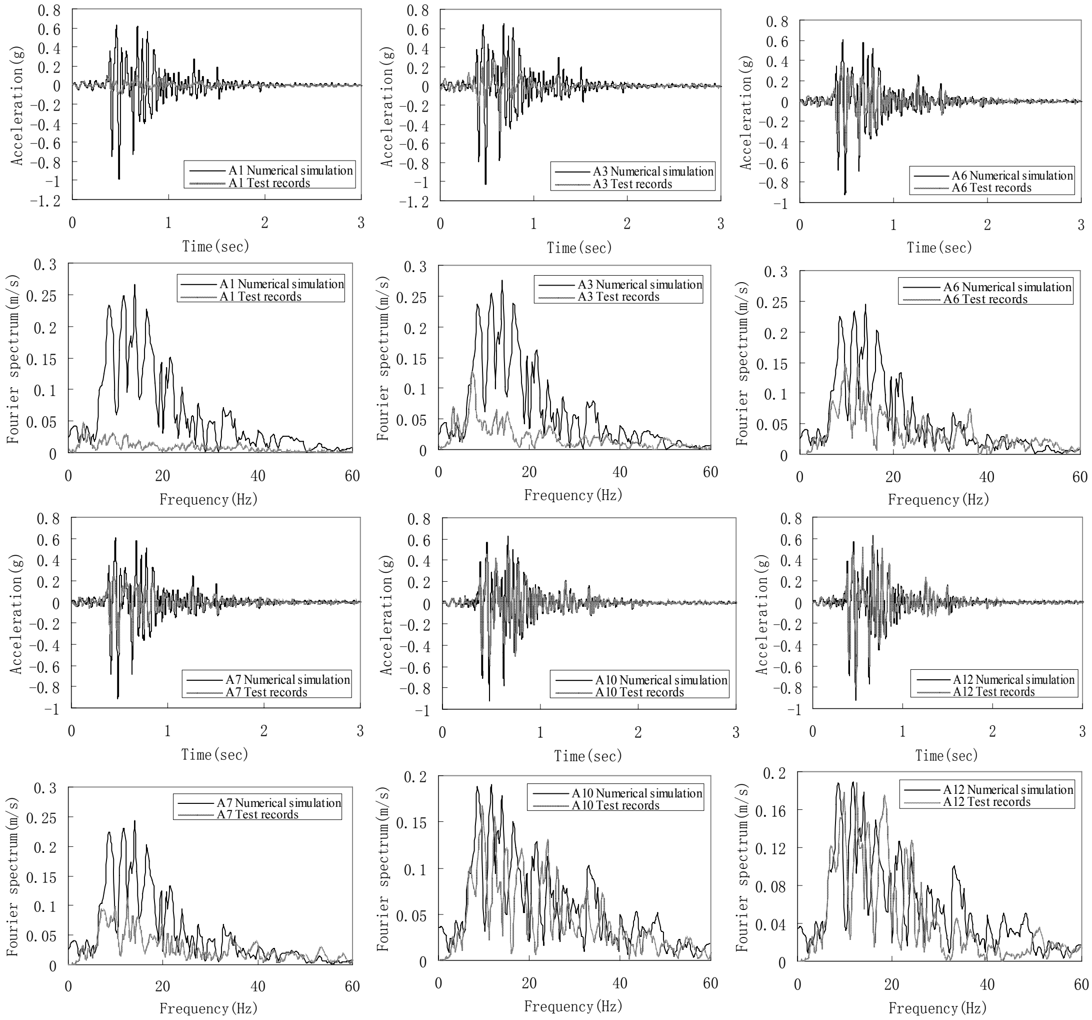
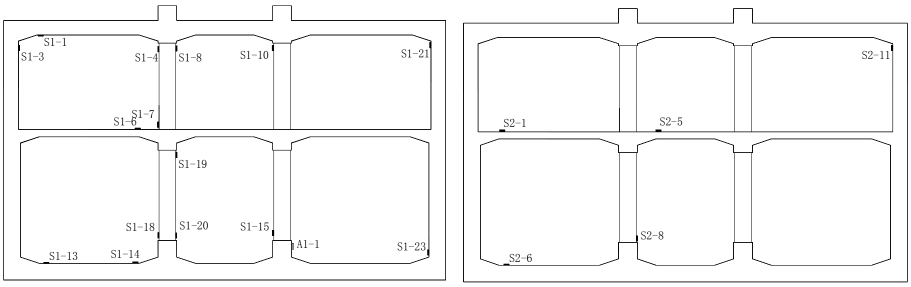


Fig.6 Acceleration time-history and Fourier spectra in different depth of model site unde C-K3 test condition



(a)Main observation section (b)Assistant observation section

Fig.7 Distribution map of normal strain sensors in sections of subway station

The strain amplitudes at different positions of station under Kobe wave is listed in Table.5. The numerical simulation results and test records under El-Centro wave and Nanjing artificial wave are almost as same as results under Kobe wave. It can be found that there is difference between numerical simulation results and test records. The reason is related with epoxy coatings of strain gauges area, and the characteristics of ground motion had also some effect on the station structure. Though there is some difference between numerical simulation results and test records, their seismic response general law is basically the same. The strain amplitude of the columns is obviously higher than those of other components. The strain amplitude of bottom layer columns is obviously higher than those of upper layer columns. The strain amplitude of the bottom of side walls is obviously higher than that of the top of side walls. The strain amplitude of boards is relatively smaller. It is identical with the analysis results for the earthquake damages of Dakai subway station: under horizontal ground motion, the strain amplitude of cross positions is high relatively, and the internal force of the columns and cross positions between side wall and bottom board is obviously higher than others.

Table 5 Strain amplitude at different positions of station under Kobe earthquake record (unit: με)

Measure position	C-K1		C-K2		C-K3	
	Simulation	Test	Simulation	Test	Simulation	Test
Left end of left span on roof(S1-1)	0.45	2.08	0.86	1.92	1.26	1.76
Right end of left span on middle slab(S1-6)	1.75	2.88	3.26	2.72	4.81	2.72
Left end of left span on middle slab(S2-1)	1.88	2.08	3.51	2.08	5.18	2.24
Left end of left span on bottom(S1-13)	1.78	2.72	2.97	2.88	4.46	2.72
Right end of left span on bottom(S1-14)	0.87	2.56	1.66	3.52	2.2	3.52
Top of upper layer column(S1-4)	6.44	16	11.61	20.96	19.82	23.52
Bottom of upper layer column(S1-7)	6.88	12.16	12.38	13.44	22.15	13.92
Top of bottom layer column(S1-19)	11.53	24.96	28.93	26.08	31.9	35.36
Bottom of bottom layer column(S1-20)	12.25	14.72	27.24	16	47.21	17.92
Top of side wall(S2-11)	0.54	3.52	0.96	3.84	1.32	3.36
Bottom of side wall(S1-23)	2.68	5.92	4.88	7.2	7.21	5.92

4.CONCLUSION

This paper introduces the contrastive analysis between the numerical simulation results and large-size shaking table test records. The results show that simulation results are basically identical with the test records. It indicated that the calculation model could simulate dynamic characteristics of soil, dynamic interaction of station structure and soil, dynamic response of station structure. At the same time, the results validated the feasibility of the test and the reliability of the test results.

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