SHAKING TABLE TEST ON IMMERSED TUNNEL SUBJECTED TO UNIFORM SEISMIC LOADINGS

Hongjuan CHEN[1], WeimingYan[2], Shicai CHEN[3], Xueming ZHANG[4]

[1] *Associate professor, Institute of Geophysics, China Earthquake Administration, Beijing 100081, China,chenyu94@163.com*
[2] *Professor, Beijing Key Laboratory of Earthquake Engineering and Structural Retrofit, Beijing university of technology, Beijing 100124, China, yanwm@bjut.edu.cn*
[3] *Professor, Beijing Key Laboratory of Earthquake Engineering and Structural Retrofit, Beijing university of technology, Beijing 100124, China, csc@bjut.edu.cn*
[4] *Lecturer, Key Laboratory of Roads and Railway Engineering Safety Control (Shijiazhuang Tiedao University), Ministry of Education, Shijiazhuang, Hebei Province ,050043, China, zxmsll@126.com*

Abstract

Taking Zhoutouzui Immersed Tunnel project in China as the background, a series of shaking table tests on immersed tunnel model are conducted under uniform seismic loadings using the shaking table testing system with 9 sub-tables in Beijing University of Technology. The tests are performed using a rigid prefabricated continuous model box with dimensions of 7.7 meters long, 3.2 meters wide and 1.2 meters high. The test system is subjected to strong ground motions from El Centro, Kobe and Tianjin records. The three ground motions were scaled to three levels (0.25, 0.75, and 1.5g). Through the tests, dynamic response of the immersed tunnel model are obtained, and its dynamic variation laws are given. The partial test results are analyzed, including acceleration response on model structure, force and deformation at model joints. The test results can guide immersed tunnel design, provide theoretical basis for revision of the seismic code, accumulate information to establish the analysis theory and design method, and understand the possible damage mechanism of underwater tunnel structures. And also, it can provide reference for similar research.

Keywords: shaking table test; immersed tunnel; seismic; dynamic response

1. Introduction

It has been more than 100 years since the world's first immersed tunnel built in 1910 which was cross the Detroit river. Compared with the methods such as open excavation and shield tunneling, the immersed construction has the advantages of shallow overburden, low requirement for geological conditions, good waterproof performance, safe construction, parallel operation, short construction period and low cost. Once used, it is rapidly developed. Up to now, more than 130 immersed tunnels have been built around the world [1-3]. At present, 18 immersed tunnels have been built in China. The Hong Kong–Zhuhai–Macao Bridge consists of one immersed tunnel with a total length of 5990 m which is the world's only deep - buried large - section sedimentation pipe project [4]. This marks a new level of installation for China's deep-sea tunnels. Construction of immersed tunnels started late but has developed rapidly in China.

A number of researchers have delivered large amounts of publications on the seismic design and analysis of immersed tunnels. Jun-Hong Ding (2006) [5] presented a three-dimensional numerical simulation method for large-scale seismic response calculation based on an immersed tunnel in Shanghai, China. Ioannis Anastasopoulos (2007) [6] investigated the seismic response of a very-deep immersed tunnel, under the simultaneous action of longitudinal, transversal, and vertical seismic excitation. Jakob Hausgaard Lyngs (2008) [7] dealed with the model accuracy for seismic design of immersed tunnels through comparative analyses of a closed form solution, a Winkler-type model, and a full three-dimensional continuum model. R.S. van Oorsouw (2010) [8] studied the behaviour of the segmental immersed tunnel subjected to seismic loading and especially on the sensitive segment joint. Based on the literature reviews, current parallel studies on seismic design and analysis of immersed tunnels are limited to theoretical and numerical approaches, less literatures are based on experiment. S.Okamoto (1973) [9] built a three-dimensional models of a subaqueous tunnel on a shaking table and vibrated for the purpose of investigating the dynamic behaviour of the tunnel, but the effect of the joint was not considered. Haitao Yu (2018) [10] carried out a series of multi-point shaking table tests on a long immersed tunnel designed for the Hongkong-Zhuhai-Macau linkage (HMZ linkage) under non-uniform seismic excitations.

In the paper, a model tunnel joint was designed, a series of shaking table tests were carried out. Through the tests, the dynamic performance of immersed tunnel and its joints were studied.

2. Experimental setup

2.1 Shaking table

The shaking table tests were carried out using the shake-table array system at Beijing University of Technology. There are a total of nine independent sub-tables. Every sub-table is one meter by one meter square. According to different requirements, several sub-tables can be selected to carry out different tests.

The working frequency ranges from 0.1 to 50 Hz. The shaking table vibrates with two maximum horizontal direction accelerations of full load 1.5g. In the tests of this paper, there were four sub-tables in total. They were arranged in a straight line, and the two adjacent sub-tables were spaced 1m apart, as shown in Fig.1. Furthermore, the verifications of the shake tables were done in the literature [11].

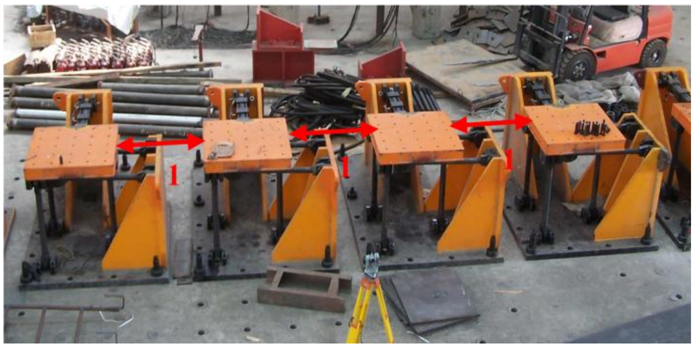


Fig. 1 –Shaking table array (unit: m)

2.2 Model soil container

There must be a container to put the soil in it just because the soil is involved in the underground structure shaking table test. There was a rigid prefabricated continuous model soil container with dimensions of 7.7 meters long, 3.2 meters wide and 1.2 meters high was designed for the test, as shown in Fig. 2.

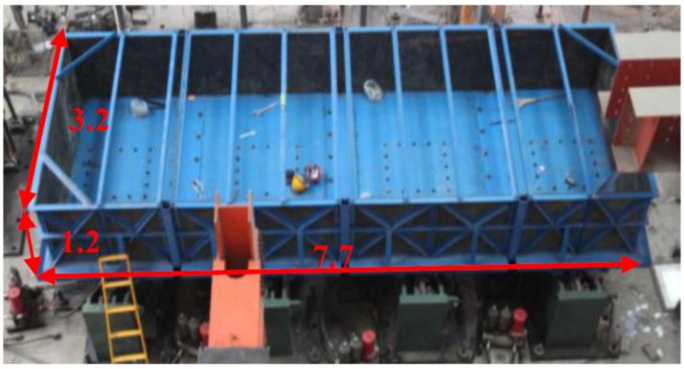
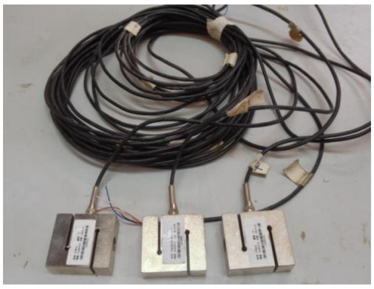


Fig. 2 –Soil container (unit: m)

2.3 Sensors and data acquisition system

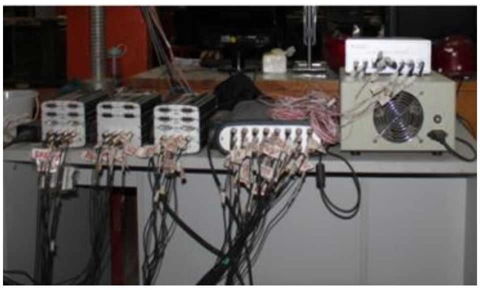
To study the dynamic response of the soil, model structure and the joints, accelerometers, force sensors and laser displacement meters were used. There were 56 accelerometers, 12 force sensors and 3 laser displacement meters were used in total. Data acquisition system is Imc device and sample frequency ranges from 200 to 1000 Hz. Sensors and data acquisition system can be seen from Fig.3.

(a) accelerometers



(b) force sensors

(c) laser displacement meters

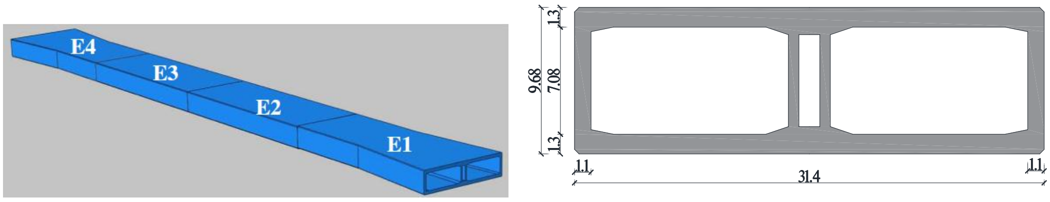


(d) data acquisition system

Fig. 3 –Sensors and data acquisition system

3. Test design

Taking the Zhoutouzui immersed tunnel of Guangzhou in China as the background, there are 4 immersed segments (E1, E2, E3 and E4) and each with length of 85 m, of which the E1 and E4 are variable cross-section segments. The height of the tunnel is 9.68 m. The standard width of the tunnel is 31.4 m and the maximum width of the tunnel is 39.36 m. The layout and standard cross-sectional design of the Zhoutouzui immersed tunnel are presented in Fig. 4.



(a) 4 segments of 85m length each (b) Standard cross-section

Fig. 4 –The graph of the immersed tunnel (unit: m)

3.1 Scale factor design

According to similarity theory of the Buckingham π law, three aspects of the simulation of the structure should be considered primarily: geometric similarity, physical similarity and mechanical similarity. The scale factor design should be based on the size and bearing capacity of the shaking table, size of the soil container, boundary effect, and convenience of model manufacturing. The length scale factor is set to 1/60. The scale factors of the model structure and soil are listed in Table 1.

Table 1 – Chemical composition of cement samples

Physical quantities	Similitude relations	Model structure	Model soil
Length	S_L	1/60	1/60
Linear displacement	$S_\delta = S_L$	1/60	1/60
Equivalent density	S_{ρ_e}	2	0.65
Elastic modulus	S_E	1/4	1/12.4
Duration	$S_T = S_L\sqrt{S_{\rho_e} / S_E}$	0.047	0.047
Frequency	$S_\omega = 1/S_T$	21.28	21.28
Acceleration	$S_a = S_E / (S_L S_{\rho_e})$	7.5	7.5

3.2 Model structure

The model structure was manufactured by micro-concrete, of which the reinforcement was made of galvanized steel wire. The manufacturing process of the model structure is presented in Fig.5.

(a) The template and wire (b) The all template (c) Formwork construction (d) Tunnel model casting

Fig. 5 –The manufacturing of the tunnel model

3.3 Model soil

In the test, sawdust mixed clay soil was used. The mixture ratio of the sawdust and prototype soil was 1:3.The details of the soil can be seen from the literature [12]. Fig. 6 presents the completed model site.

Fig. 6 –The completed model site

3.4 Model joints

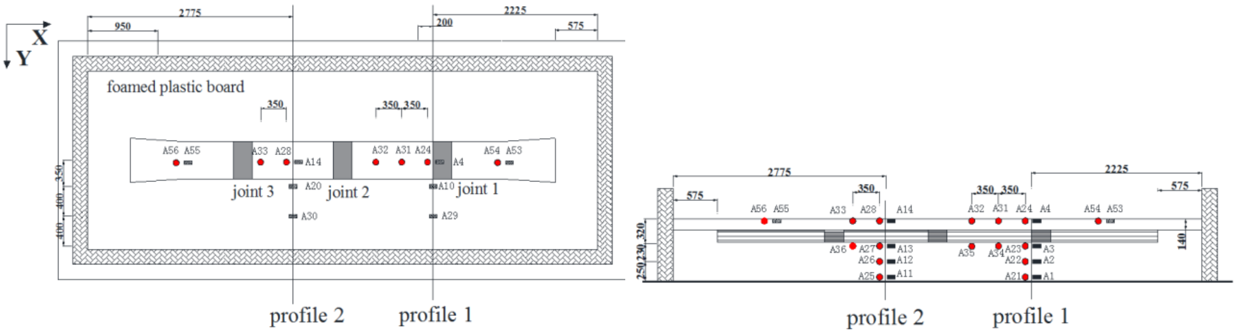
The immersed tunnel was divided into four sections, of which three joints were present between the sections. For the test, a new kind of model joint was designed and made. The detail information can be seen in the literature (Chen H.J., et al. 2017). The model joint can be seen in Fig. 7.

(a) Rubber waterstop (b) Shear key (c) Whole graph

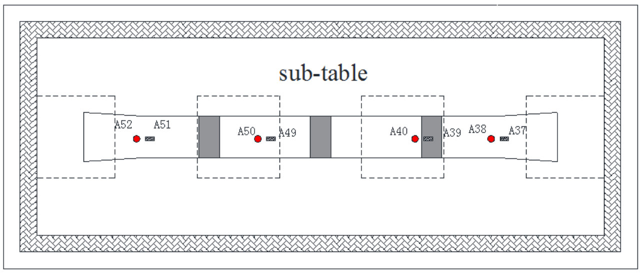
Fig. 7 –The joint immersed tunnel model

3.5 Layouts of sensors

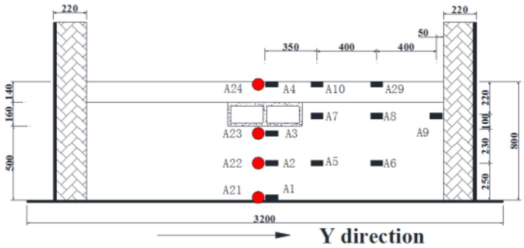
A series of shaking table tests were conducted under uniform earthquake excitation using the multiple shaking table testing system at the Beijing University of Technology. The sensor arrangements are presented in Fig. 8 and Fig. 9. In the tests, accelerometers were arranged in the soil and on the model structure. The accelerometers in the X- and Y-directions in Fig. 8 are represented by red dots and black rectangles, respectively. The force sensor layout is presented in Fig. 9. The laser displacement meters (see Fig. 10) were arranged in each joint. There were three joints in total.



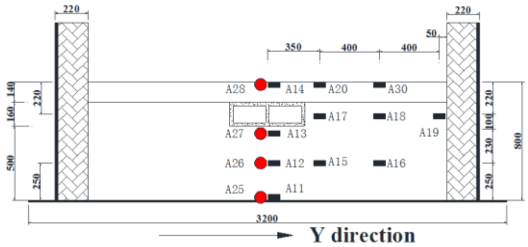
(a) On the soil surface (b) In the longitudinal profile



(c) On the model tunnel

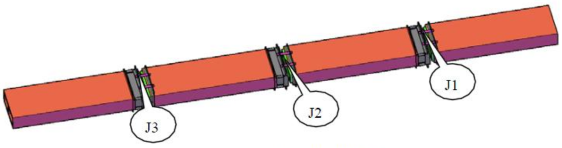


(d) Profile 1.

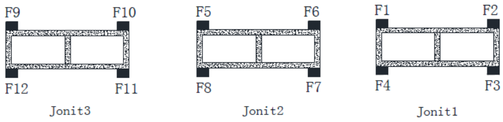


(e) Profile2.

Fig. 8 –The accelerometers arrangement (unit: mm)



(a) Layout of the joints



(b) Layout of the sensors

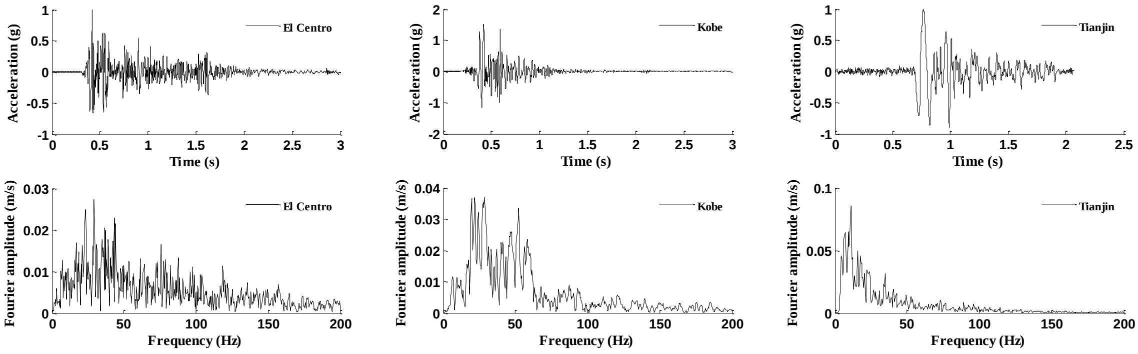
Fig. 9 –Force sensors arrangement of the joints

(a) Laser displacement sensor (b) The receiving signal end

Fig. 10 –The laser displacement meters arrangement

3.6 Loading method and test cases

In the tests, El Centro, Kobe and Tianjin records were selected. Fig.11 presents the acceleration time histories and Fourier spectra of the three records. The three ground motions were scaled to three levels (0.25, 0.75 and 1.5g). The shaking table vibrated in X direction and Y direction that were parallel and perpendicular to the axial direction of the model structure, respectively. Table 2 gives the test cases.



(a) El Centro (b) Kobe (c) Tianjin

Fig. 11 –Acceleration records and Fourier spectra of the input motions on the shaking table

Table 2 –Test cases

Seismic input	**The peak ground acceleration (PGA) (g)**		
	Test No.1	Test No.2	Test No.3
White noise	0.07	0.07	0.07
El Centro	0.25	0.75	1.5
Kobe	0.25	0.75	1.5
Tianjin	0.25	0.75	1.5

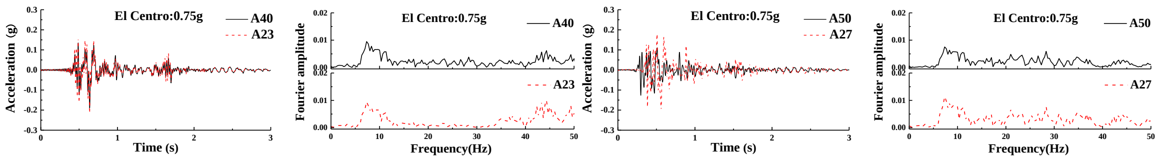
4. Test result and analysis

The boundary effects of the soil box are unavoidable in all soil-structure interaction dynamic tests. According to the literature [12], boundary effect of the model box used is small and negligible in the test.
The test results are presented from the following three aspects. In the paper, limited to the space, only the results of the X direction are analyzed.

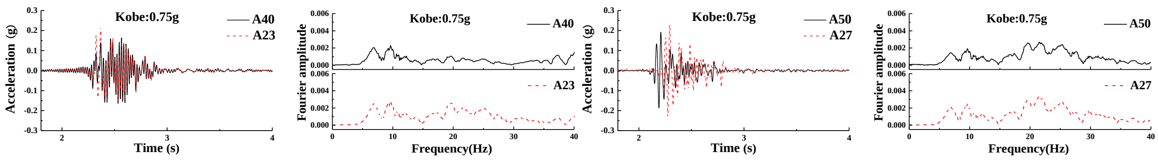
4.1 Acceleration response of the model soil and structure

To compare the two accelerometers between the tunnel model structure and the surrounding soil, accelerometer A40 on E2 segment of model tunnel structure and A23 in soil nearby , accelerometer A50 on E3 segment of model tunnel structure and A27 in soil nearby are chosen. The acceleration time histories and their Fourier spectra are depicted in Fig. 12 for the vibration in X direction when the earthquake intensity is 0.75g.

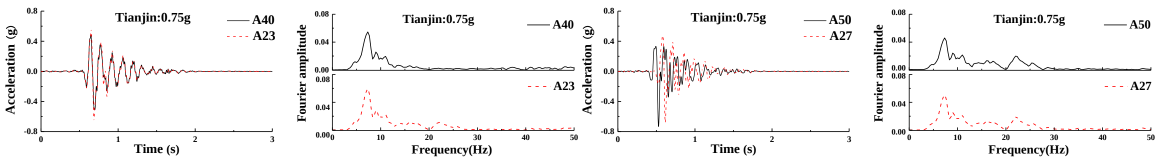
It can be seen from these figures (Fig.12) that :(1) Waveforms of response accelerations from sensors on structure and in soil match very well. And it means the response accelerations phase synchronization primitives. But acceleration amplitude on structure is smaller than that in surrounding soil, this is in line with the actual observation results in actual earthquakes. (2) The Fourier amplitude spectra of the response accelerations keep good shape similarity in soil and on structure. The above phenomena, due to the constraints of the surrounding soils, the seismic response of underground structures does not vibrate along with its own features, but is subject to the seismic response of the surrounding soils, it has to do with other researchers' test conclusion (literature [9]). (3) There are differences of acceleration time histories and their Fourier spectra among different segments.



(a) El Centro



(b) Kobe



(c) Tianjin

Fig. 12 –Accelerations on structure and in soil under seismic excitation

4.2 Results of the joints force

Under different ground motion, the extreme values of different force sensors are shown as in Fig. 13.

It can be seen from Fig. 13: (1) Peak values of force time histories under different seismic excitation have similar change rule. (2) With the increase of input intensity, the absolute values of peak force are increased. (3) The maximum and the minimum values of each force time history are distributed symmetrically along the neutral axis. (4) Peak values of force time histories measured from force sensors No.7 and No.9 are larger than others.

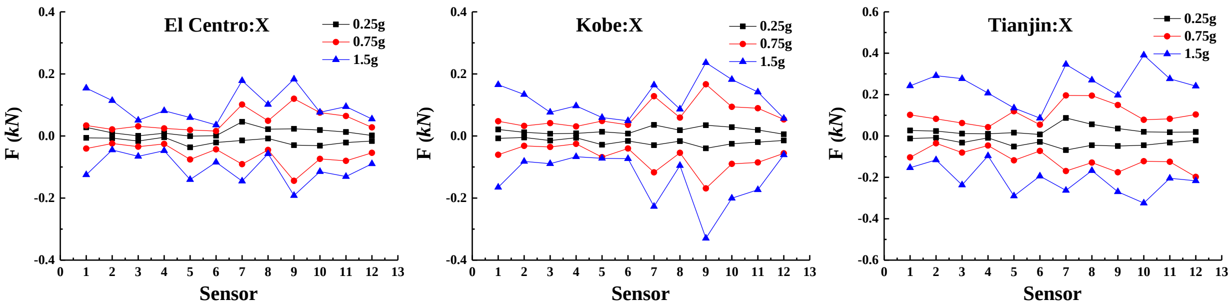


Fig. 13 –Force peak values of different sensors under different seismic excitations

4.3 Results of the joints displacement

Deformation of different joints under different intensities of different seismic excitations can be seen from Fig.14.

Fig. 14 shows that: (1) Under different seismic excitations, positive and negative direction displacement change trend of each joint basic parallel (i.e., tension or compression). (2) Under different seismic intensities earthquake excitation, the change tendency of different joint displacement basically follows the largest joint displacement of J1 joint, the minimum of J2 joint. It dues to the J2 connector located in the middle, so that the change rule of the tunnel along the longitudinal deformation is more coordination. (3) Under different intensities of seismic excitations, the change rule of different joint displacement are consistent in the two situations. (4) Under X direction seismic input, the maximum joint displacements are

0.61 mm, 0.50 mm and 0.69 mm under El Centro, Kobe and Tianjin seismic excitations, respectively. According to the similarity relation conversion, the prototype tunnel joint maximum tensile displacement are 36.6 mm, 30 mm and 41.4 mm, less than the precompression of 50 mm, so that the joint water stop is in a safe range and will not leak.

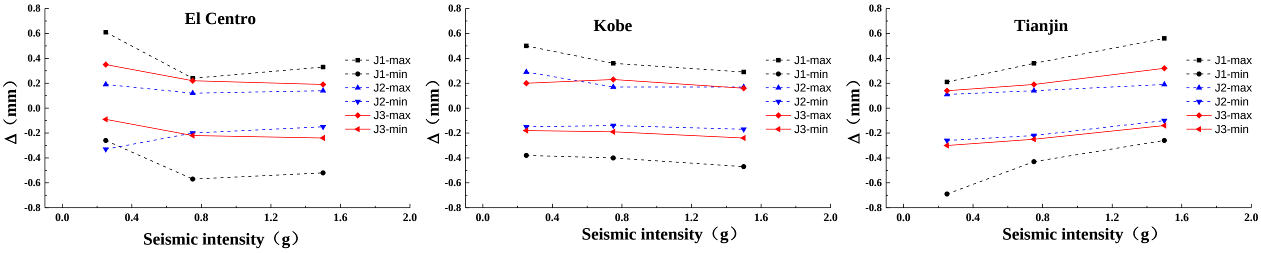


Fig. 14 –Displacement of different joints under different seismic excitations

5. Conclusions

Detailed information about design of the shaking table model test was given. Dynamic characteristics of the model tunnel and its joints were studied. The following conclusions are drawn from the results of the study.

(1) The seismic response of underground structures don't vibrate along with its own features, but is subject to the seismic response of the surrounding soils.

(2) The maximum values of force time histories are different under different seismic excitations. The maximum values of force time histories of the middle joints are larger.

(3) The model joints will not leak in the tests.

6. Acknowledgements

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