

A shaking table test of immersed tunnel-joints-soil under earthquake excitation

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Abstract

In order to obtain the seismic response of the immersed tunnel and its joints under seismic action, with Zhoutouzui Immersed Tunnel project in China as the background, a series of shaking table tests on immersed tunnel-joints-soil were done. The paper introduces the test comprehensively which includes the determination of similarity relation, the design of model soil container, the manufacturing of model structure, the layout of the sensor monitored points, the preparation of model soil, the loading plan of the input motions, the measuring method of the force and displacement between the joints, and so on. Some of the test results are given and analyzed. And also the dynamic response rules of the immersed tunnel and its joints are summarized.

Keywords: immersed tunnel; joint; shaking table test; Zhoutouzui Immersed Tunnel; dynamic response



1. Introduction

Since 1910, the world's first immersed tunnel - the Detroit river railway tunnel across the United States and Canada construction of complete, it has a history of more than 100 years up to now. Compared with other methods such as excavation method, shield method of building underwater tunnel, immersed method has many advantages which are with shallow cover thickness, low requirements for geological conditions, good waterproof performance, construction safety, parallel operation, short construction period and low cost and so on. Once used, it gets rapid development. So far, the world has been built more than 130 immersed tunnels [1 ~ 4]. China's first immersed tunnel was built in 1972, Hongkan Immersed Tunnel in Hong Kong. The first immersed tunnel in Chinese mainland was built in 1993, Guangzhou pearl river immersed tunnel. Now, there are 5 immersed tunnels in Hong Kong, one in Taiwai, 9 immersed tunnels compeleted and 3 immersed tunnels under construction in Chinese mainland. Remarkable Hongkong-Zhuhai-Macao Bridge engineering including 5664 m immersed tunnel, is currently the world's only buried back silting sectional immersed project, it will be the world's longest highway engineering, marking the Chinese deep tunnel installation to a new height [5]. Although the construction of immersed tunnel in China lately started, the development was rapid.

Shaking table model test is an important way to do the antiseismic research of underground structures. It can better grasp of the underground structure seismic response characteristics, so widely used. At present the researchers around the world are working on shaking table test research.

Much work has been done in the field of shaking table test on underground structure, e.g. literatures $[6 \sim 9]$, but special research about underwater immersed tunnel experiment is less. In literature [10], three-dimensional models of a subaqueous tunnel were built on a shaking table and vibrated for the purpose of investigating the dynamic behaviour of the tunnel. Maybe this was the first shaking table test on underground structure. At present, most research on immersed tunnel mainly based on the numerical simulation, e.g. [11 ~ 14], the results depend on the validation of tests.

An immersed tunnel is composed of several sections in connection, the connection part of the joint is the weak link of the immersed tunnel waterproof, and joints are the key of the immersed tunnel engineering. Joints design of one immersed tunnel, the component configuration is reasonable, the joints construction quality can meet requirement relates to the success or failure of a immersed tunnel.

Considering that the lack information of shaking table test about immersed tunnel and its joint at current, taking Guangzhou Zhoutouzui Immersed Tunnel as the background, the tests were done under uniform earthquake excitation of horizontal longitudinal and horizontal transverse, and some regular conclusions were got. All of these can provide strong technical support for earthquake-resistance calculation of the immersed tunnel, 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.

2. Background

According to the literature [15], Zhoutouzui Immersed Tunnel is located in the west navigation channel of the Pearl River in Guangzhou. It is between the Guangzhou Pearl River tunnel, which is the first immersed tunnel in mainland of China, and Hedong Bridge. It is another river channel that is contact with the Fangcun Village in Liwan District and Haizhu District. It is about 1.4 km from upstream of the Pearl River tunnel, and 2.2 km from downstream of the Hedong Bridge. It starts with road intersection of Flowers Avenue and Hualei Road in Fangcun Village in Liwan District. And then, it goes to the east village avenue down through the Pearl River, and connects with Hongde Road overpass in Haizhu District through the ramp inside loop, and crosses Hongde Road and connected with the planning T13 road. It ends with the intersection of T13 road and Baogang Road, the length of this project measures 3253.034 m, of which 340 m long for immersed part [4].

There are 4 immersed segments with each length of 85 meters. The graphic design of Zhoutouzui Immersed Tunnel is shown in figure 1.



3936

Fig. 1 –The graphic design of Zhoutouzui Immersed Tunnel [cm]

3. Experimental setup

3.1 Shaking table array

A series of shaking table tests were conducted at the multiple shaking table array which is composed of nine subshaking tables $(1m \times 1m)$ in Beijing University of Technology. Design load of each sub-shaking table is 5 ton. The maximal displacement is ± 7.5 cm, maximum speed of 60 cm/s, maximum acceleration (full load) to 1.5 g X and Y, operating frequency range: $0.1 \sim 45$ Hz. The system can realize two levels to the switch and the vertical combination of a variety of ways, and it can impose arbitrary waveform of natural earthquake affected synthetic seismic waves. In this test, four sub-shaking tables were used, and they were arranged in a straight line. The spacing distance of the two adjacent sub-shaking tables is 1 meter, as shown in figure 2.



Fig. 2 – The shaking table array of Beijing university of technology

3.2 Model box

To simulate seismic response of the semi-infinite space using shaking table tests, the model box used to fill soil has great influence to the rationality of the test results, and can even lead to test result far away from the actual situation. At present, the underground structure shaking table test mainly use the model of soil box can be divided into rigid model box, flexible cylindrical model box, laminar shear model box and so on. Considering the laboratory conditions and test a long line of immersed tube tunnel structure with the scope of soil region is larger, the rigid soil box can meet the test requirements. In this paper, a prefabricated box continuous rigid body model was developed. All the tests were performed using a rigid prefabricated continuous model box with dimensions of 7.7 meters long, 3.2 meters wide and 1.2 meters high.

In order to prevent the model at the bottom of the soil slip, covered with gravel at the bottom. In order to minimize vibration direction on rigid boundary influence on structure dynamic response, side wall around the model box lined with polystyrene foamed plastic board. Except in the direction of vibration on both ends of the box wall of chlorobenzene thin foam board account size and reserve size along the height direction, soil size 6.86 m $\times 2.36$ m $\times 2.36$ m, the size of the corresponding prototype foundation is 411.6 m $\times 141.6$ m $\times 48$ m. The model box is as shown in figure 3.



Fig. 3 – The graph of model box

3.3 Model soil

The dynamic similarity relation between the prototype and the model is the key to reliability of shaking table model test results. At present, the similarity relation of model structure can be satisfied, while the foundation soil mainly uses the prototype soil directly. Such as this kind of model tests, the stiffness of structure, quality and other characteristics according to the similarity criterion for the reduction, and the foundation soil has no reduction. It makes the model and prototype of stiffness ratio of soil and structure not consistent, so the model test results of soil - structure dynamic interaction law will inevitably with the prototype soil - structure dynamic system have bigger difference, even the wrong conclusions.

At present, it can reduce the stiffness and mass ratio through adding some other materials in the soil, there are several ways to change the related parameters of soil: (1) adding iron powder and iron sand in the soil, the density of soil increases, but the modulus basicly remains the same, and cost of this method is higher, materials is not convenient and iron is easy to rust, and the shaking table would be overloaded; (2) adding rubber particles in the soil, the density and modulus of soil can be reduced; (3) adding sawdust in the soil, the shear modulus of soil can obviously decrease, soil density also can have a certain degree to reduce, and sawdust with low cost, conveniently. In this paper, the third method was used. Clay in the Beijing area as the prototype, compound sawdust and adding proper amount of foundation soil water preparation test model.

Based on the principle of structure and foundation soil matched similarity relation, soil mixed with sawdust is used to design the model foundation soil of a long linear small scale underground structure shaking table test through predominant period similarity relation. Dynamic property of model soil mixed with different proportion of sawdust was conducted by resonant column. Using the equivalent linear constitutive model, the dynamic parameters (Gmax and G/Gmax- γ curves) of the prototype soil and mixed soil are given. And furthermore, the proportion of sawdust was determined for the model soil. According to the tests, the ratio of sawdust: soil: water is 1:3:2.7. Detailed design of model soil can consult literature [16]. The model soil is as shown in figure 4.

According to the shaking table ability, experimental model selecting geometric similarity ratio for 1:60, according to the law of Bukingham, taking geometrical size 1, density ρ and elastic modulus E as the basic physical quantities, similitude ratios of physical quantity can be seen from table 1.



Fig. 4 – The completed model site



Table 1 Similitude relations of model structure and soil			
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	$S_{ ho_e}$	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

3.4 Model structure

Structure model manufactured by micro-concrete, reinforcement are made of galvanized steel wire, through the preparation of the model structure of the particle concrete mixing proportion of cement (425 #): yellow sand, lime: water is 1:6.0:0.6: 0.5, its elastic modulus is 7410 N/ mm2, cube compressive strength of 5.679 N/ mm2 was roughly the same density and prototype concrete, so the similitude ratio of density is 1 and elastic modulus is 1/4. Due to the overall size of model is small, the model of the production process, fully consider the influence of production condition, using the template and wire mesh production process, and in the process of making arrangement hook angle steel, easy to simulate immersed tunnel steel welding joint, manufacturing process of model structure is as follows, as shown in figure 5.



(a) The template and wire (b) The all template



3.5 Model joint

There are four sections and three joints between sections of the immersed tunnel. The axial stiffness of joints are provided by shear keys and cables, the total tensile stiffness of 38 sets of cables is 83406.2 kN/m. Through finite element simulation results, the compression stiffness can be simplified to bilinear model, and because the initial amount of compression of 50 mm, so the joint axial compression stiffness is the main compression stiffness, joint tensile stiffness mainly for pretension cables stiffness. Test model for the convenience of water stop making remove point, simplify the effect of pre compression, structure model manufactured by micro-concrete, embedded angle steel, and compared with the steel shell welding, water stop is simplified to and tunnel cross section, the thickness of the rubber ring for 2 cm, firm bonding of steel shell and the end. Horizontal and vertical shear key is thickness of 2 mm rectangle ring, and end at the end of the steel shear key shell welding is firm, on the other side of the free end, make them free to insert a cross section of the larger rectangle steel ring. Prestressed steel cable simplified as fine screw, as shown in figure 6. In figure 6 (c), one end with water -stop, and using the fine screw prestressing, in the process of hoisting and tunnel embedment, in order to prevent the deformation of tunnel joint is too large and with thick screw fixation, loosen it before backfill . At the other end to install pressure sensors to measure the axial force of the tunnel, install four, each joint are distributed in the upper and lower end.



(a) Rubber waterstop



(b) Shear key



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(c) Whole graph

Fig. 6 – The joint model of immersed tunnel

3.6 Layout of sensors

A series of shaking table tests on free field soil site and unfree field soil site were conducted under uniform earthquake excitation at the multiple shaking table testing system in Beijing University of Technology. Sensors arrangement can be seen from fig .7 and 8. Limited space reason, seismic response of free field tests is not analyzed. Only the acceleration sensor arrangement on soil surface is given, to examine the influence degree of Boundary effect of the model container. In fig.7 and 8, the acceleration in X direction and Y direction were represented by red dots and black rectangles respectively. Force sensors layout can be seen from fig .9.



Fig. 7 -Acceleration sensors arrangement of free field soil surface





(c)

Fig. 8 – Acceleration sensors arrangement of unfree-field: (*a*) on soil surface ;(*b*) in longitudinal profile; (*c*) on the model tunnel; (*d*) observation surface 1-1 ;(*e*) observation surface 2-2.



Fig. 9 – Force sensors arrangement of the joints: (a) joints; (b) sensors arrangement.

3.7 Input earthquake

Taking the El-Centro $\$ Taft $\$ Tianjin and Guangzhou artificial Earthquake acceleration records as prototype wave, time histories of these earthquake waves were constructed and adopted as the inputs for the test. Acceleration records and Fourier spectra of input motions can be seen from fig.10. According to the seismic design code of China, Guangzhou Zhoutouzui Immersed Tunnel project is located in 7 degrees area, the peak acceleration of minor, moderate and major earthquake are 0.035 g and 0.10 g and 0.22 g corresponding . amplitude modulation after the corresponding test of small, medium and strong earthquakes were 0.2625 g and 0.75 g and 1.65 g, vibration table maximum acceleration of 1.5 g, so the step by step loading method was used with imported vibration peak acceleration, in turn, is 0.1, 0.25 g , 0.5 g , 0.75 g, 1 g, 1.25 g and 1.5 g. The ground motion input is in the longitudinal direction (X) and lateral direction (Y).



Fig.10 -Acceleration records and Fourier spectra of input motions on the shaking table surface



4. Boundary effect of the model container

In order to make the vibration of the box not affect the vibration of the soil, fundamental frequency of the model box must be far away from the fundamental frequency of model ground. Due to the fundamental frequency single model ground cannot be measured, so the need to make the model box base band away from the model box - soil system fundamental frequency.

Boundary effect of soil container is unavoidable in all soil-structure interaction dynamic tests [16–18]. In essence, the fundamental frequency problem of model box and site belongs to the boundary effect problem. The fundamental frequencies of both the empty lamina box and the soil-box system are tested using random excitation with limited amplitude. For empty lamina box, spectra analysis is performed on the time history of sensors installed on the box to identify the predominant frequency, and a similar process is performed using the response of A4 (A14) and A24 (A28) for the soil-box system. It is found that the fundamental frequencies of the empty shear box are 15.63 Hz and 13.87Hz in X and Y directions, and the fundamental frequencies of the box-soil system are 10.74Hz and 7.81 Hz in X and Y directions, respectively.

Expedition is the boundary effect of the methods used by assuming that provided the soil vibration response of the center for the standard, with the boundary point of vibration and the corresponding comparison, through the two response signal proximity to judge the size of the boundary effect, when the closer the two signals is that the smaller the boundary effect. Evaluation of the boundary effect is usually adopted by assuming that provided the soil vibration response of the center for the standard, with the boundary point of vibration and the corresponding comparison, through the two response signal proximity to judge the size of the boundary point of vibration and the corresponding comparison, through the two response signal proximity to judge the size of the boundary effect, when the closer the two signals is that the smaller the boundary effect.

In order to quantitatively study the boundary effect, use the method in literature [8]. An index based on 2-Norms deviation is introduced to quantify the boundary effect of the model box. The index μ is calculated using the following equation(1):

$$\mu = \frac{\|x_i - x_j\|}{\|x_i\|} = \sqrt{\frac{\sum (x_i - x_j)^2}{\sum (x_i)^2}}$$
(1)

where x_i , x_j are quantities of reference signal and comparison signal, respectively. x_i , x_j can be taken as the response time history or even the spectra curve. 2 - norm deviation μ is of mean square approximation concept in statistical, it reflects the difference between two signals. If μ value of the two signals equals to zero, two signals are exactly the same.

Under X direction seismic excitation, the acceleration time history of A28 were regarded as basic signals. Under Y direction seismic excitation, the acceleration time history of A4 $_{\times}$ A14 and A33 were regarded as basic signals. Fig. 11 shows 2-norm index μ calculated using acceleration responses in free-field tests. From Fig. 11,we can see 2 - norm of near the model box border station A36 and A29, A30 slants big, this is because the rigid model adopted in this paper box. Other 2 - norm values of each measuring point deviation mainly around 0.5, based on literature [8], boundary effect of the model box used in the test of is small, can accept that basicly.



Fig.11 -Norm-2 index in X direction and Y direction tests: (a) X direction test and (b) Y direction test.



5. Model test result and discussion

5.1 Acceleration response of model soil and structure

In order to compare the two accelerations between the tunnel model structure and the surrounding soil, accelerometer A40 (A39) on E2 segment of model tunnel structure and A23 (A7) in soil nearby, accelerometer A50 (A49) on E3 segment of model tunnel structure and A27 (A17) in soil nearby are chosen. The acceleration time histories and their Fourier spectra are depicted in Figs. 12(a) and (b) for the vibration in longitudinal direction and transversal direction for PGA=0.5g, respectively.

It is seen from these figures that :(1) waveforms of acceleration sensors on structure and in soil match very well. And it means the acceleration responses phase synchronization primitives. But structural acceleration amplitude is smaller than the acceleration amplitude surrounding soil near, this is in line with the actual earthquake observation. (2) Soil and the structure of the Fourier amplitude spectrum of the acceleration keep good shape similarity. The above phenomenon, due to the constraints of the surrounding soils, the seismic response of underground structures is not vibrate along with its own features, but is subject to the seismic response of the surrounding soils, it has to do with Shunzo Okamoto and Choshiro Tamura test conclusion. (3) There are differences of acceleration time histories and their Fourier spectra between different segments. (4) The observations in transversal vibration are the same.



(b) transverse direction (Y), 0.5g



Fig.12 –Accelerations of structure and soil under seismic excitation : (a) longitudinal direction; (b) transverse direction

5.2 Force results of joints

Under different ground motion in the longitudinal and transverse earthquake excitation, the extreme values of different force sensors are shown as in figure 13.



Fig.13 -Force peak value of different sensors under the longitudinal and transverse seismic excitations

It can be seen from figure 13(a): (1) peak values of force histories under different earthquake excitation have similar change rule. (2) With the increase of input intensity, the absolute value of peak force is increased. (3) The maximum and the minimum values of each force history are distributed symmetrically along the neutral axis. (4) peak values of force histories measured from No.7 and 9 force sensors are larger than other under El Centro, Taft and Guangzhou artificial earthquake excitation.(5) peak values of force histories measured from No.7, No.9 and No.10 force sensors are larger than other under Tianjin earthquake excitation.

It can be seen from figure 13(b): (1) peak values of force histories under different earthquake excitation have similar change rule. (2) With the increase of input intensity, the absolute value of peak force is increased. (3) The maximum and the minimum values of each force history are distributed symmetrically along the neutral axis. (4) under El Centro and Taft earthquake excitation, peak values of force histories measured from No.1,No.5 and10 force sensors are larger than other.(5) peak values of force histories measured from No.5 and No.7 force sensors are larger than other under Tianjin earthquake excitation. (6) under Guangzhou artificial earthquake excitation, peak values of force time histories are larger than other under Tianjin earthquake excitation. (6) under Guangzhou artificial earthquake excitation other under Tianjin earthquake excitation. (7) the maximum values of force time histories are the largest under Tianjin seismic wave excitation, followed by Guangzhou artificial seismic excitation, the values under El Centro and Taft seismic excitation are smaller.

5.3 Displacement results of joints

Deformation of different joints under different intensity of longitudinal and lateral earthquake excitation can be seen from Figure 14.





Fig.14 –Displacement of different joints under longitudinal and transverse seismic excitation

The figure 14 shows: (1) under different seismic wave excitation, positive and negative direction displacement change trend of each joint basic parallel (i.e., tension or compression); (2) under different seismic wave, the different intensity earthquake excitation, the change tendency of different joint displacement basically follows the J1 joint displacement, the largest J3 joint displacement, J2 connector, minimum displacement due to the J2 connector is located in the middle, so that the change rule of make the tunnel along the longitudinal deformation more coordination; (3) under different seismic wave, the different intensity earthquake excitation of different joint displacement change rule in vertical and horizontal earthquake under the action of the results are consistent; (4) under longitudinal and transverse earthquake action, the maximum joint displacement is 0.63 mm and 0.61 mm respectively, according to the similarity relation conversion prototype tunnel joint maximum tensile displacement were 37.8 mm and 36.6 mm, less than the precompression of 50 mm, so the joint water stop in a safe range will not leak.

6. Conclusions

A series of shaking table tests were conducted to investigate the performance of tunnel, especially the joints, under uniform seismic excitation. Detailed information about design of model box and model soil has been described and should be useful for further similar investigations. Performance of the designed model box has been checked through free-field test. A 2-norm index is used to quantify the boundary effect. The results demonstrate that the designed model box does not impose significant boundary effect. A new type of model joint was designed in this paper, and force and displacement of joint were measured successfully. The location of bearing force and deformation of joint can guide the design, so can strengthen the corresponding measures through the results.

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