Shaking Table Model Test Design for Utility Tunnel

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Abstract. Three methods are mainly used in the seismic research of underground engineering, including theoretical research, numerical calculation and experimental research. In this paper, a detailed design of a utility tunnel shaking table test is carried out. First, the selection of the shaking table, model box and sensor were analyzed and studied. Then the test scheme was designed in detail. The design of the test scheme mainly includes 4 aspects. These 4 aspects are the similarity ratio design, the reinforcement of model structure, the input seismic wave and the sensor arrangement. In the design of similarity ratio, E, ρ, L and a are the basic quantities. The other variables are converted by the idea of combination dimensional analysis and kinetic equation. The height of the model box is not more than 2.5m according to the previous research results. The height of the model box should be smaller, and the height of the model box is 1.8m by calculation. The reinforcement ratio of the equal area is adopted. El-Centro wave, Kobe wave and Taft wave were selected in the experiment. One way step by step loading system was adopted in the test. At last, the position and quantity of the 4 kinds of sensors used in the experiment were studied, and the detailed layout of sensors were given.

1. Introduction

With the development of urbanization, the demand for underground space has been further increased. The development of underground space has been transformed from a single underground structure to a comprehensive utilization of underground space [1]. In 1995, a large number of underground structures such as subway station, utility tunnel damaged in Kobe earthquake. This has aroused people's attention to the seismic research of underground structures [2-4]. Shaking table test is an important technical means for the seismic research of underground structures. Since the invention of the shaking table, a large number of different types of shaking table tests of underground structures have been carried out by scholars at home and abroad. At the same time, many achievements have been achieved [5-11]. However, these studies are mainly focused on the foundation of high buildings and subway stations, and less research on the seismic test about the utility tunnel. In this paper, a detailed design of a utility tunnel shaking table test is made, which mainly includes the selection of the test equipment and the design of the test scheme. Based on this test design, the next step of the shaking table test will be carried out.

2. Selection of test equipments

2.1. Shaking table

The parameters of shaking table that proposed in this experiment are as follows:

The size of the table is 4.1m x 4.1m. The maximum horizontal acceleration of the table is 1g and the maximum overturning moment is 80 t*m.
2.2. Model box
The model box is the container of the soil sample and the model structure in the shaking table test, which is mainly controlled by the table size and the bearing capacity of the shaking table. The commonly used model boxes at home and abroad are divided into rigid model box, layered shear model box and cylinder flexible model box. The utility tunnel in this experiment is a long line underground structure. The length direction of the model is larger than the other two directions. Therefore, rigid model box and layered shear model box are considered. In the early stage of the shaking table test, the rigid model box was mostly used. The rigid model box is welded with angle steel and steel plate to form rigid frame of box wall. When the vibration is full, the overall stiffness is large and the lateral deformation is small. The reflection of seismic waves on the box wall is large, and the boundary effect is large. In order to better simulate the boundary conditions of the prototype site and the shear deformation of the soil layer and reduce the boundary effect of the model, a layered shear model box is put forward. The layered shear model box is used in this experiment because it can simulate the layered shear of the soil layer and reduce the reflection of seismic waves.

2.3. Testing elements
The purpose of this test is to measure the seismic response of the utility tunnel. In this test, the main measurements are the acceleration response of the structure and soil layer, the lateral deformation of the soil layer, the structural strain, and the soil pressure at the contact surface of the soil layer. The test elements required for the test data types include accelerometers, strain gauges, displacement meters, and earth pressure boxes.

3. Design of test scheme

3.1. Similarity ratio
The purpose of the model similarity design is to determine the relationship between the model and the prototype, and then the results of the prototype structure are calculated by the results of the model test. The similarity theory used in similar design is the Bockingham π theorem. The method used in the design is considered by the dynamic equation and the dimensional analysis method [12]. The structural dynamic equations are as follows:

\[ m(a+g) + cv + k \mu = 0 \]  

According to Formula 1, we can see that the dynamic problem mainly simulates inertia force, damping force and restoring force. In the similarity ratio design, the geometric size, elastic modulus, density and acceleration of the model are taken as the basic design parameters. The constraint equations of the similarity relation are:

\[ \frac{\lambda_g}{\lambda_p, \lambda_s, \lambda_r} = 1 \]  

3.1.1. Similarity ratio of length (\( \lambda_L \)). In this test, the cross section size of the utility tunnel is 6m × 6m. This experiment is a cross section shaking table test. The purpose is to measure the response of the utility tunnel under transverse seismic action, so we only input horizontal seismic waves. In order to meet the two working conditions of the test design and consider the economy at the same time, two model boxes are arranged on the shaking table. Previous studies have shown that the scale structure of subway and other underground structures can be observed when the distance between the ends of the cross-section is greater than 0.76 times the width of the structure, and the measurement results meet the plane strain assumption. Geometric similarity ratio of model structure is 0.1. The structure length is:

\[ L = 2 \times 0.76 \times W + l \]
L is the calculation length of the utility tunnel. W is the calculation width of the utility tunnel. l is an intermediate measurement area. The length of the model is calculated by equation (3).

\[ L = 2 \times 0.76 \times 600mm + 500mm = 1412mm \] (4)

Because the size of shaking table is 4m x 4m, the transverse length of the model box is 1.5m for the convenience of making the model box. The model box is arranged in the shaking table as shown in Figure 1.

The height of the model site is not too high after meeting the test requirements. Shi gives the equation for the maximum height of the model [13].

\[ H_{max} = \frac{c}{\rho(a_{max} - gtan \phi)} \] (5)

The maximum height of the general site is 2.5m by equation (5). The height of the site was 1.8m in this test.

3.1.2. Similarity ratio of elastic modulus (\( \lambda_E \)).
In this test, the concrete is particle concrete, and steel wire is used instead of steel bar. \( \lambda_E \) is 0.2.

3.1.3. Similarity ratio of density (\( \lambda_a \)).
Bring the values of \( \lambda_L \) and \( \lambda_E \) into formula 2 to get \( \lambda_a = 2 / \lambda_p \). Based on the weight of added weight the model structure can be converted to the corresponding structural reaction.

3.2. Model structure reinforcement
In this test, the reinforcement ratio of the equal area is adopted. The reinforcement ratio of the bending steel bar of prototype structure is:

\[ \rho^1 = \frac{A^1_I}{b^1h^1} \] (6)

The reinforcement ratio of the shear steel bar of prototype structure is:

\[ \rho^1_{sv} = \frac{A^1_{sv}}{b^1s^1} \] (7)

The reinforcement ratio of the shear steel bar of model structure is:

\[ \rho^2 = \frac{A^2}{b^2h^2} \] (8)

The reinforcement ratio of the shear steel bar of prototype structure is:
\[ \rho_{\text{av}}^2 = \frac{A_{\text{av}}^2}{b^2 s^2} \]  

(9)

According to the principle of equal area reinforcement, \( \rho^1 = \rho^2 \) and \( \rho_{\text{av}}^1 = \rho_{\text{av}}^2 \) should be met at this time.

### 3.3. Seismic Wave

#### 3.3.1. Selection of seismic waves

In this experiment, three kinds of seismic waves are selected as the input waves of the shaking table, which are El wave, Kobe wave and Taft wave. The acceleration time curve and Fourier spectrum curve of the three waves are shown in Figure 1.

**Figure 2. Seismic wave acceleration time history curve and fourier spectral curve**

#### 3.3.2. Test loading system

One way step by step loading system is adopted in the test. The test loading system for shaking table test of the utility tunnel is shown in Table 1.

| Sequence number | Type     | Code | Peak acceleration | Sequence number | Type     | Code | Peak acceleration |
|-----------------|----------|------|-------------------|-----------------|----------|------|-------------------|
| 1               | White noise | W1   | 0.05              | 14              | El wave | E14  | 0.4               |
| 2               | El wave   | E2   | 0.05              | 15              | Kobe wave | K15  | 0.4               |
| 3               | Kobe wave | K3   | 0.05              | 16              | Taft wave | T16  | 0.4               |
| 4               | Taft wave | T4   | 0.05              | 17              | White noise | W17  | 0.05              |
| 5               | White noise | W5   | 0.05              | 18              | El wave | E18  | 0.6               |
3.4. Sensor placement

According to the purpose of the test, two observation sections are set up in each model system, as shown in Figure 1. The purpose of this experiment is to measure the reaction of the structure under the earthquake (acceleration response, structural strain response, soil displacement). According to the data types needed to be measured in the experiment, the required test components are accelerometer, concrete strain gauge, steel strain gauge and displacement meter. According to the previous investigation and analysis, 26 accelerometers (A1-A23, AS1-AS3), 7 earth displacement meters (L1-L3), 5 earth pressure gages (P1-P5) and 28 concrete strain gages (S1-S28) were identified in main section. The layout of the test element for the main section is shown in Figure 3. 16 accelerometers (A24-A36, AS4-AS6), 4 earth displacement meters (L8-L11), 3 earth pressure gages (P6-P8) and 17 concrete strain gages (S29-S43) were identified in supplementary section. The layout of the test element for the supplementary section is shown in Figure 4. In the Figure 3 and 4, A represents the accelerometer, L represents the displacement meter, P represents the earth pressure gauge, and the S represents the strain gauge.

|   |   |   |   |   |
|---|---|---|---|---|
| 6 | El wave | E6 | 0.1 | 19 | Kobe wave | K19 | 0.6 |
| 7 | Kobe wave | K7 | 0.1 | 20 | Taft wave | T20 | 0.6 |
| 8 | Taft wave | T8 | 0.1 | 21 | White noise | W21 | 0.05 |
| 9 | White noise | W9 | 0.05 | 22 | El wave | E22 | 0.8 |
| 10 | El wave | E10 | 0.2 | 23 | Kobe wave | K23 | 0.8 |
| 11 | Kobe wave | K11 | 0.2 | 24 | Taft wave | T24 | 0.8 |
| 12 | Taft wave | T12 | 0.2 | 25 | Taft wave | T25 | 1.0 |
| 13 | White noise | W13 | 0.05 | 26 | White noise | W26 | 0.05 |

Figure 3. The instrument layout of the main observation section

Figure 4. The instrument layout of the supplementary observation section
4. Conclusion
In this paper, a detailed design of a shaking table test for utility tunnel is carried out. In this experiment, the shaking table is selected a one-way vibration table with the table size of 4.1m×4.1m, and the model box is a layered shear model box. The test sensors include accelerometer, displacement meter, earth pressure box and strain gauge. In the design of similarity ratio, \( \lambda_L = 0.1, \lambda_E = 0.9 \) and \( \lambda_a = 2/\rho \). The reinforcement ratio of the equal area is adopted in the calculation of the model reinforcement. In this experiment, three kinds of seismic waves are selected as the input waves of the shaking table, which are El wave, Kobe wave and Taft wave. The specific loading process has been given in this paper. At the end of this paper, the detailed layout and number of each test element for two observation sections are given. The experimental design of this paper is based on the preliminary investigation and based on the requirements of this test, which is the basis for the next experiment.

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References
[1] Bo W 2013 Exploration and Practice of the Development and Utilization of Urban Underground Space (Beijing: China University of Geosciences)
[2] Senzai S 1997 J. A Study of The Damage of Subway Structures During the 1995 HANSHIN—AwpUI eanh—quake. Cement and Concrete Composites. 19 233.
[3] Changshi P 1996 J. Current Situation of Research on Earthquake Resistance of Tunnel and Underground Structures. World Tunnel. 7
[4] Haiyang Z, Shaoge C and Guoxin C 2008 J. Numerical Simulation and Analysis of Earthquake Damages of Dakai Metro Station Caused by Kobe Earthquake. Rock and Soil Mechanics. 29 245
[5] Jun C, Xiaojun S ang Jie L 2010 J. Shaking Table Test of Utility Tunnel Under Non-uniform Earthquake Wave Excitation. Soil Dynamics and Earthquake Engineering. 30 1400
[6] Bining G and Dapeng Z 2002 J. Experimental Study on Dynamic Interaction of Underground Structure and Soil. Journal of China Three Gorges University. 493
[7] Linde Y, Qianqian J and Yonglai Z 2003 J. Shaking Table Test on Metro Station Structures in Soft Soil. Modern Tunnelling Technology. 7
[8] Qianqian J 2002 Shaking table model test on the metro station structures (Shanghai: Tongji University)
[9] Guoxing C, Xi Z, Zihhua W 2010 J. Shaking Table Model Test of Subway Station Structure at Liquefiable Ground under Far Field and Near Field Ground Motion. Journal of Zhejiang University. 44 1955
[10] Chen J, Luzhen J, Jie L and Xiaojun S 2012 J. Numerical simulation of shaking table test on utility tunnel under non-uniform earthquake excitation. Tunnelling & Underground Space Technology. 30 205
[11] Guoxing C, Zihhua W, Xi Z 2010 J. Development of Laminar Shear Soil Container for Shaking Table Tests. Chinese Journal of Geotechnical Engineering. 32 89
[12] Pengbo M 2016 The Design and Analysis of The Shaking Table Test of The Subway Station Model in The Loess Site (Xi’an: Chang’an University)
[13] Xiaoping W 2002 Experimental Study on Sandy-Soil-Pile Structure Interaction By shaking Table (Shanghai: Tongji University)