Experimental Study on Vibration Platform under the Coupling Action of Soil-Metro Upper Cover Structure

Xuechuan Han*, Lianjin Tao, Shao An and Yu Zhang
Key Laboratory of Urban Security and Disaster Engineering of Ministry of Education, Beijing University of Technology, Beijing 100124, China
Email: tshanxuechuan@126.com

Abstract. In order to study the seismic response law of the Upper Cover Structure station system, the shaking table test was carried out on the silty sand site with the subway superstructure system and single subway station structure as the research objects. Firstly, the general situation of shaking table test is introduced. Then, the seismic response of subway station structure is studied from two aspects including acceleration and strain, and the test results are compared. The test data show that: (1) With the increase of input seismic intensity, the acceleration peak value of soil and monitoring points of the same structure increases gradually, while the acceleration amplification coefficient decreases gradually. (2) With the increase of earthquake intensity, the tensile strain amplitude of the superstructure-subway station structure increases gradually. In the model, the tensile strain amplitude at the end of the column is the largest, followed by the side wall and the floor is the smallest. (3) The acceleration and strain of the superstructure-subway station system are less than those of the single subway station structure, in which the acceleration variation law is roughly the same. The difference of strain amplitude gradually increases with the increase of earthquake intensity, and the change rate of strain peak value gradually increases and converges.

Keywords. Upper cover integrated structure, seismic response, shaking table test.

1. Introduction
With the rapid development of economy, urban land resources are in serious shortage. Comprehensive utilization of land and improvement of land use efficiency have increasingly become the key issues in subway construction. The subway upper cover structure strengthens the integrated planning of subway station and surrounding land and the comprehensive utilization of station land, improves the comprehensive development and utilization level of subway station, and makes rational use of urban resources [1]. At present, the government encourages the main body of rail transit to give full play to its own advantages, it can be realizing a new model of joint development of underground rail transit structure and ground structure, optimizing the single construction mode of urban rail transit stations, increasing the supporting functions of stations and ancillary ground structures, promoting land composite utilization and improving land use efficiency. The subway upper cover superstructure may become one of the main trends in the structural design of rail transit in the future.

In recent years, many researches have carried out several shaking table tests on subway underground structures, and obtained many valuable research results [2-3]. However, in view of the development level and structural forms of subway underground structures, the researches mostly focused on the seismic performance of subway station structures or tunnels such as single, close-fitting and crossing. Because the above-ground-underground structure system is a very complex interaction
system, the researches were relatively few and mostly limited to numerical simulation. For example, Zhang Tianyu et al. [4] studied the seismic response characteristics of subway station and its superstructure system based on ABAQUS software, and discussed the influence of vertical ground motion effect and transfer beam stiffness. Li Yantao et al. [5] carried out shaking table test of tunnel-soil-adjacent superstructure system in soft soil. Pitilakis et al. [6] studied the seismic response law of underground circular tunnel, and considered the influence of single and multiple adjacent surface structures respectively. Robb et al. [7] designed the model soil with dynamic strength as the main similar parameter, and studied the subway-structure interaction under earthquake, and the test results reached the expected strength range. Choi [8], Hu [9-10], Boulanger [11], etc. have summarized some empirical laws by comparing the seismic responses of underground structures and ground structures.

The seismic response characteristics and failure mechanism of subway superstructure are still unclear. The construction industry has relevant regulations for urban rail transit structures and concrete structures of above-ground buildings, but there is a lack of guidelines for seismic design of subway superstructure, which is incompatible with the scale and prospect of integrated subway superstructure construction in China. In order to deeply study the seismic response characteristics and failure mechanism of subway superstructure, the shaking table test of subway superstructure (YT) and single subway station structure without superstructure (DT) were carried out, and the structural parts of subway station were studied in acceleration and strain, and the results of the two tests were compared.

2. Summary of Vibration Table Test

In order to study the seismic response law of single subway station structure and superstructure, shaking table tests of soil-single subway station structure and soil-superstructure subway station structure were designed respectively.

2.1. Shaking Table Test System and Model Box

The test was carried out on the shaking table system of the Key Laboratory of Urban Security and Disaster Engineering of the Ministry of Education, Beijing University of Technology. The main parameters of the shaking table are as follows: The size of the table is 3 m×3 m. The maximum load can be applied to 10t. The maximum input acceleration can be applied to ± 1 g. The maximum horizontal displacement of the table can reach ± 127 mm. The working frequency can reach 0.1 Hz-50 Hz. The dynamic load can only be applied in the horizontal direction of the model box. The layered shear model box, developed by the research group, is adopted in this test. At the same time, the model box can simulate the damping boundary of soil.

2.2. Shaking Table Test System and Model Box

| Table 1. Scale relationship of Subway Station model structure system. |
|-----------------|-----------------|-----------------|-----------------|-----------------|
| Physical properties | Physical quantity | Similar symbol | Similarity relation | Similarity ratio |
| Geometric performance | Length | S_L | S_L | 1/40 | 1/4 |
| Area | S_A | S_L^2 | 1/1600 | 1/16 |
| Linear displacement | S_L | S_L | 1/40 | 1/4 |
| Strain | S_E | S_E/S_E | 1 | 1 |
| Elastic modulus | S_E | S_E | 1/4 | 1/4 |
| Mass density | S_P | S_P | 1 | 1 |
| Quality | S_m | S_m/S_m | 1/64000 | 1/64 |
| Time | S_T | S_T | 0.158 | 0.5 |
| Power performance | Frequency | S_f | S_f^{1.5}Sa^{-0.5} | 6.32 | 2 |
| Acceleration | S_a | S_a | 1 | 1 |
Based on Buckingham $\pi$ theorem, the similarity relation design is carried out [12]. Starting with dynamic dimensional analysis, the length, elastic modulus and acceleration are selected as the basic physical quantities of model structure. The density, acceleration and shear wave velocity are selected as the basic physical quantities of model foundation, as shown in table 1.

2.3. Manufacturing of Model Structure

According to the structural size, characteristics of the prototype subway station and the requirement of similarity ratio in the design test, the prototype structure is simplified that the structural model is made of granular concrete with compressive strength of 7.1 MPa, elastic modulus of 6.9 GPa and Poisson's ratio of 0.16. According to the strength similarity ratio, the reinforcement ratio of the specimen should remain unchanged. The model structure size and cross-section shape are shown in figure 1.

![Cross-sectional view of station](image1)

![Longitudinal section of station](image2)

Figure 1. Structure model size and cross section shape.

2.4. Production of Model Soil

The model foundation is made of homogeneous soil, which is taken from the Caoqiao Station of Beijing Rail Transit New Airport Line. The model soil is prepared by layered compaction method, and the dried and screened fine sand is evenly spread in the model box by hoisting funnel. Through this method, the compactness of the model soil can be guaranteed. The material parameters of model soil are shown in table 2.

| Name             | $\rho$ (kg/m$^3$) | $c$ (kPa) | $\phi^{\circ}$ | $N_{\text{max}}$/% | $N_{\text{max}}$/% | $V_S$(m/s) | $E$/MPa | $\nu$   |
|------------------|-------------------|-----------|----------------|---------------------|---------------------|------------|---------|---------|
| Silty fine sand  | 1730              | 26        | 24             | 1.14                | 0.62                | 235        | 272     | 0.34    |

2.5. Sensors Arrangement

The main monitoring contents of shaking table test in covered subway station include acceleration response law of covered subway station structure model and foundation soil, dynamic interaction between soil and covered subway station structure, strain response law of covered subway station structure and lateral deformation law of model foundation soil, etc. The sensors used in this test include acceleration sensor A, optical fiber strain gauge S, soil pressure gauge P and laser displacement gauge J. The sensors arrangement in this model foundation and structure are shown in figures 2-3.
2.6. Seismic Wave Selection and Loading Conditions

Considering the influence of near and far site vibration on the superstructure of subway station, three seismic waves with different epicentral distances, including octagonal Shifang wave, Mingshan wave and Fengxiang wave, are selected. Among them, the octagonal Shifang wave belongs to near-field vibration, the Mingshan wave belongs to medium site vibration, and the Fengxiang wave belongs to far-field vibration. The three seismic wave acceleration time history curves are shown in figure 4. During the shaking table test, the first 80 s with strong seismic wave is intercepted as input seismic wave. When the peak acceleration changes, the white noise scan is performed to determine the change of the natural vibration characteristics of the model system. The shaking table test was carried out with step-by-step loading method. The peak accelerations of input seismic waves are adjusted to 0.1 g, 0.3 g, 0.5 g, 0.7 g and 1.0 g, respectively.

![Figure 2. Upper Subway Station model foundation sensor layout.](image1)

![Figure 3. Upper Subway Station sensor arrangement.](image2)

![Figure 4. Acceleration time-histories of bedrock ground motion.](image3)
3. Analysis of Test Results
Because of the limited space, this section studies the structure of subway station with integrated superstructure from acceleration and strain, and the test results are compared with the single station structure.

3.1. Acceleration Response Analysis of Model Soil
In order to compare the acceleration of the model soil under different earthquake conditions and the structural conditions of the subway station with integrated superstructure, figure 5 shows the acceleration peak value and acceleration amplification coefficient curves of the monitoring points (JA7, JA8, JA9, JA10 and JA11) in the model soil. The ratio of the peak acceleration of each monitoring point to the peak acceleration of JA16 is defined as the acceleration amplification coefficient of this monitoring point. It is worth noting that Fengxiang wave has pulse acceleration, which leads to larger instantaneous displacement of the shaking table. Due to the limitation of the maximum displacement of the shaking table, the maximum acceleration of Fengxiang wave can only be increased to 0.3 g.

It can be seen from figure 5 that the acceleration peak value of the same monitoring point of the model soil gradually increases with the increase of the input earthquake intensity, while the acceleration amplification coefficient gradually decreases. Under different earthquake conditions, the acceleration peaks and amplification coefficient of monitoring points in model soil show different laws with the decrease of buried depth due to the influence of seismic wave characteristics. When the input earthquake intensity is small (0.1 g, 0.3 g), the acceleration peaks and amplification coefficient of monitoring points in model soil gradually increase with the decrease of buried depth, and the acceleration amplification coefficient are basically greater than 1. When the input earthquake intensity is larger (above 0.3 g), the acceleration peak value and amplification coefficient of the monitoring points in the model soil under the action of Mingshan waves decrease at first and then increase, while Shifang waves show an S-shaped trend, which shows a trend of increasing at first, then decreasing and finally increasing. The monitoring points with acceleration amplification coefficient less than 1 gradually increase. This shows that when the input earthquake intensity is small, the model soil is in elastic state, and the seismic wave has a significant amplification effect in the process of upward propagation from the bottom. With the increase gradually of the input earthquake intensity, the model soil changes from elastic state to elastic-plastic state. The nonlinear phenomena near the monitoring points A8 and A9 of the model structure become more prominent.

![Figure 5](image_url)

**Figure 5.** Peaking acceleration and acceleration amplification factor of points of model soil.
Figure 6 shows the acceleration time history curves and Fourier spectrograms of the model soil monitoring points JA1, JA2 and JA3 under two test conditions, and DT-SF-3-JAX represents the acceleration time history of measuring point X in shaking table test of single subway station when the 0.3g octagonal shifang wave is input. Among them, the JA1 is located at the above of the model structure and close to the ground surface. The JA2 and JA3 are located at the below of the model structure and the same vertical position with the monitoring point JA1. By comparing the acceleration time-history curves and Fourier spectrum distribution laws of monitoring points JA1, JA2 and JA3, we can explain the difference of the influence of the model structure on the seismic wave propagation process under different test conditions.

It can be seen from figure 6 that under different earthquake intensities, the acceleration time history curve and Fourier spectrum curve of the monitoring points with the same station structure under DT and YT conditions are basically the same, and both the acceleration peak appear at the same time. The dominant frequencies of the same monitoring points are basically the same, and the main frequency ranges all show the trend of shifting from high frequency to low frequency. The peak acceleration of monitoring points in DT and YT conditions increases gradually with the increase of input earthquake intensity, and the peak acceleration in YT condition is smaller than that in DT condition. Acceleration peaks and amplification coefficient of YT condition is smaller than those of DT condition, and the difference of acceleration amplification effect increases gradually with the increase of buried depth. This is because the energy distribution of seismic waves in the main frequency range under DT condition is relatively concentrated, which leads to more obvious acceleration amplification effect, and it can be seen from JA1 acceleration spectrogram.

![Acceleration Time History Curves and Fourier Spectra](image-url)

**Figure 6.** Time histories and Fourier spectra of model soil.

### 3.2. Acceleration Response Analysis of Model Structure

Figure 7 shows the variation curves of acceleration peak value and acceleration amplification coefficient at each monitoring point of the middle column of the model subway station under different earthquake conditions and different earthquake intensities. The ratio of the peak acceleration of the monitoring point to the acceleration of the vibration table monitoring point JA16 is defined as the acceleration amplification coefficient of the monitoring point.
It can be seen that the acceleration peak value of the monitoring points of the middle column of the model station increases gradually with the increase of the input earthquake intensity. The acceleration peak value of the top monitoring point JA20 of the middle column is the largest, while the acceleration peak value of the bottom monitoring point JA22 is the smallest. The acceleration amplification coefficient of the middle column under seismic wave conditions in various position shows a decreasing trend with the increase of input seismic intensity, which is mainly because the model structure gradually changes from elastic stage to elastic-plastic stage when the seismic intensity gradually increases. The damage of the middle column is more serious, accompanied by the phenomenon of stiffness degradation. When the input seismic wave intensity is small, the acceleration peak value and acceleration amplification coefficient of the middle column monitoring point are quite different.

3.3. Strain Response Analysis of Model Structure

Considering the limited of number of data acquisition channels of measurement equipment and meeting the test requirements to the maximum extent, the model structure is approximately considered as the symmetrical seismic response law, and the left half of the subway station is selected as the research object to study the strain response law of the structure. Tensile damage mainly occurs in concrete structures, and the degree of compression damage is small. Therefore, this section mainly analyzes the seismic response of model structures under tensile strain. Figure 8 shows the tensile strain amplitude distribution of the main observation surface of the model structure under different ground motions.

It can be seen that the peak strain of each measuring point of the model structure is octagonal Shifang wave (near field wave) > Mingshan wave (middle field wave). Under the effect of same seismic wave, the tensile strain amplitude of the model structure increases gradually with the increase
of seismic intensity. The tensile strain amplitude at the end of the middle column is the largest, followed by the side wall and the floor is the smallest. This is because the cross-sectional area of the middle column is small and there is no resistance provided by the surrounding soil, which leads to relatively insufficient bearing capacity, and it is more likely to be damaged under horizontal earthquake. It shows that the middle column is still the weak part in the seismic design of the superstructure integrated subway station structure. The strain amplitudes at the top and bottom of the side wall and central column are significantly larger than those in the middle part, which is due to the synchronous movement of the model structure and soil under the earthquake action, which leads to the shear deformation of the structure.

The tensile strain amplitudes of side wall and central column of metro station under DT test condition and YT test condition under different seismic intensity are shown in Table 3. Compared with DT test condition, the strain at monitoring points of model structure under YT test condition is relatively small. When the input seismic waves are 0.1 g, 0.3 g and 0.5 g, the strain rates under YT conditions are 1.5% ~ 3.7%, 4.1% ~ 6.0% and 6.1% ~ 7.7%, respectively. It can be seen that with the increase of seismic intensity, the strain change rate gradually increases, the change rate of strain peak value gradually increases and converges.

Table 3. Strain amplitude of points in different conditions (unit: με).

| Wave          | Location | Measuring points | Loading conditions | Rate of change 0.1g | 0.3g | 0.5g |
|---------------|----------|------------------|--------------------|----------------------|------|------|
| Shifang wave  | Wall     | S1               | DT-1               | 20.42                | 49.70| 79.52|
|               |          | S2               | DT-3               | 15.31                | 37.82| 60.51|
|               |          | S3               | DT-5               | 19.26                | 46.01| 75.22|
|               |          | S4               | YT-1               | 20.27                | 49.35| 78.96|
|               |          | S5               | YT-3               | 21.61                | 52.46| 83.94|
|               |          | S6               | YT-5               | 18.12                | 44.35| 70.96|
|               | Column   | S7               |                    | 19.69                | 47.99| 76.78|
|               |          | S8               |                    | 24.65                | 59.54| 95.26|

4. Conclusion
In this paper, taking the subway superstructure as the research object, the dynamic response law of subway station superstructure in silty sand field is studied by shaking table test method. Based on the analysis of this paper, the following conclusions can be drawn:

(1) Under the same seismic wave, the acceleration peak value and acceleration amplification coefficient of the model soil and the station structure of the covered subway station are smaller than those of the single subway station. The acceleration amplification coefficient is quite different under near-field vibration, while the acceleration amplification coefficient is less different under far-field vibration, and the difference is more obvious with the deeper the buried depth. However, the variation laws of the acceleration peak value and acceleration amplification factor are basically the same, which shows that the different structural forms have little influence on the variation laws of the site acceleration.

(2) The acceleration peak value of the same monitoring point in the subway station with integrated superstructure is roughly octagonal Shifang wave (near field) > famous mountain wave (middle field) > Fengxiang wave (far field). The variation law of the strain peak of the integrated subway station is similar to that single subway station structure, which shows that the strain peak value increases gradually with the increase of input earthquake intensity. The acceleration peak value of different seismic waves is quite different, but the difference of acceleration peak value decreases gradually with the increase of earthquake intensity.

(3) The strain peak value of each measuring point in the subway station with integrated superstructure is octagonal Shifang wave (near field) > famous mountain wave (middle field) > Fengxiang wave (far field). The variation law of strain peak value is basically consistent with that
under DT condition, indicating that the strain peak value increases gradually with the increase of input seismic intensity. Compared with DT test condition, the strain peak value of monitoring points of model structure under YT test condition is relatively small, and the change rate of strain peak value under near-field vibration is greater than that under far-field vibration. With the increase of earthquake intensity, the change rate of strain peak value gradually increases and converges.

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References
[1] Jia J 2015 Design Practice of Urban Underground Complex Shanghai: Tongji University Press.
[2] Wang Z Z, Jiang Y J, Zhu C A, et al. 2015 Shaking table tests of tunnel linings in progressive states of damage Tunn. Undergr. Pace Technol. 50 109-117.
[3] Xu H, Li T B, Xia L, et al. 2016 Shaking table tests on seismic measures of a model mountain tunnel Tunn. Undergr. Space Technol. 60 197-209.
[4] Zhang T Y and Chen Q J 2019 Seismic response analysis of earth-metro-metro station and its upper-cover structure system Mechanics Quarterly 40(3) 504-514 (in Chinese).
[5] Li Y T, Tian Y and Zong J H 2020 Shaking table test of tunnel-soil system affected by adjacent superstructure Journal of Vibration and Shock 39 (3) 233-259 (in Chinese).
[6] Pitiakis K, Tsinidis G, Leanza A, et al. 2014 Seismic behaviour of circular tunnels accounting for above ground structures interaction effects Soil Dynamics & Earthquake Engineering 67 1-15.
[7] Robb E S M, Vic C and Steven K 2010 Shake Table Testing to Quantify Seismic Soil-structure Interaction of Underground Structure Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics San Diego p 1-5.
[8] Choi J S, Lee J S and Kim J M 2002 Nonlinear earthquake response analysis of 2-D undergroundstructures with soil-structure interaction including separation and sliding at interface 15th ASCE Engineering Mechanics Conference June 2-5 Columbia University New York NY p 1-8.
[9] Huo H, Bobet A, Fernandez G, et al. 2005 Load transfer mechanisms between underground structure and surrounding ground: evaluation of the failure of the Daikai station Journal of Geotechnical and Geoenvironmental Engineering 131(12) 1522- 1533.
[10] Huo H B and Bobet A 1995 Seismic design of cut and cover rectangular tunnels-evaluation of observed behavior of Dakai station during Kobe earthquake World Forum of Chinese Scholars in Geotechnical Engineering Shanghai.
[11] Boulanger R W, Wilson D W, Kutter B L, et al. 2004 Nonlinear FEM analyses of soil-pile interaction in liquefying sand Geo technical Engineering for Transportation Projects Geotechnical Special Publication (126) p 470-478.
[12] Gao L and Zhu T 2000 Similar skills for structural dynamic model test Journal of Dalian University of Technology 40(1) 1-6 (in Chinese).