Research Article
Shaking Table Test on Seismic Response of Tunnel-Soil Surface Structure System considering Soil-Structure Interaction

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With the increasing number of underground structures traversing the surface structure, the surface and underground structures interact with each other during earthquakes, thus affecting the seismic response of the interaction system. Based on this idea, the dynamic interaction system of a tunnel-soil-surface structure is designed. The seismic responses such as acceleration, strain, and interlayer displacement angle are analyzed, and the vibration characteristics and laws of the interaction system under different seismic loads are studied through the shaking table test. The results show that the type of seismic wave has a significant impact on the seismic response of the system, in which the dynamic response of the surface structure and soil is more sensitive to the seismic wave with rich low-frequency components. The acceleration response of soil near the tunnel-surface structure area is stronger than that of soil far away from the interaction area. During earthquakes, the maximum strain of the deep tunnel appears in the region of 45° between the two sides of the lining and the vertical symmetry axis, whereas the maximum strain of the shallow tunnel close to the surface structure is different from that of the deep tunnel. For the surface structure, with the input peak acceleration increasing, the weak layer of the surface structure moves down, and the interlayer displacement angle of the middle and lower layers is significantly larger. The research results have certain reference significance for exploring the seismic response law of a tunnel-soil-surface structure interaction system.

1. Introduction

With the acceleration of urban construction, the “urban syndrome” such as tight land resources, traffic congestion, and high population density increasingly restricts social progress and economic development. Rational development and utilization of urban underground space is a necessary measure to optimize the urban spatial structure, promote the synchronous development of underground space and the whole city, and alleviate the shortage of urban land resources. Moreover, it is of great significance to improve the urban environment and achieve sustainable urban development. Therefore, the geotechnical engineering community has devoted great attention to the construction of underground structures since the 1990s. However, it is worth noting that many underground structures are located in seismic belts. When underground infrastructures are damaged during earthquakes, they will not only cause serious economic losses and heavy casualties but also have a significant impact on the social life of the cities [1–5]. As a result, evaluating the seismic performance of underground structures is important. By considering the characteristics of soil, excitation conditions of ground motions, contact conditions between underground structures and soil, and location of underground structures mainly based on numerical simulation and shaking table test, many scholars have made important contributions to this research [6–18]. Chen et al. [19] studied the failure mechanism of a frame subway station structure in the loess area through a series of large-scale shaking table tests. The test results found that the soil-structure interaction was more significant in both horizontal and vertical directions when higher PGA was input. The strain of the middle column and middle slab of the subway station was larger than that of other members. Compared with previous tests, the failure mode of the underground structure was related to the dynamic
characteristics of the soil. Tsinidis et al. [20] studied the seismic response of a square tunnel in the sand by combining dynamic centrifugal test and numerical analysis. The experimental and numerical results reported that the vibration mode of the flexible model tunnel was a rocking mode coupled with the racking distortion. The increase of the lining stiffness led to a decrease in the cracking deformation and the inward deformation of the slabs and the side walls. In addition, the soil-tunnel interface characteristics affected significantly the calculated dynamic axial force of the lining.

With the rapid development of underground structures, an increasing number of underground infrastructures have been built in prosperous areas with dense buildings, which leads to the intersection of underground structures and adjacent buildings. From a seismic point of view, the underground structure and soil have different stiffness; the interface between the underground structure and soil will scatter and reflect seismic waves, which will lead to dynamic response changes at free sites [21–26]. Thus, the existence of underground structures, especially large underground structures, will have an impact on the dynamic characteristics of the surrounding soil and then affect the response of the adjacent buildings [27–34]. The vibration caused by the inertia effect of buildings has an influence on soil, which then affects the seismic response of the underground structure [35–38]. From the above analysis, it can be seen that studying the dynamic interaction of underground structures-soil-adjacent buildings is the key to ensuring the overall earthquake-resistant and disaster-prevention capability of cities. Therefore, more scholars have begun to study this problem [39–42]. Abate and Massimino [43] used fully coupled finite element method (FEM) modeling to investigate the dynamic response among tunnel-soil-aboveground buildings. Their study found that the presence of a tunnel led to a lower acceleration ratio at the soil surface compared with free-field conditions, and building caused a decrease in soil acceleration. He [44] carried out a nonlinear analysis on a surface building-soil-underground structure interaction system. It was found that the existence of the underground structure significantly amplified the relative displacement, acceleration, and shear of the surface building. The surface building enlarged the displacement and acceleration of the underground structure. In addition, the ground structure destroyed the symmetry of the subway station, which made the strain increase of the underground structure near the side of the building more obvious. Wang et al. [45] conducted a shaking table test of an underground structure-soil-surface structure and investigated the law of the seismic response of an interaction system. In the test, organic glass was selected as the model material of the tunnel and superstructure, and only their elastic response was considered in the test. The test results showed that the existence of a surface structure suppressed the seismic response of soil and underground structures. The existence of a tunnel could amplify the response of the surface structure to a certain extent.

Because the underground structure-soil-surface structure is a very complex dynamic interaction system, most scholars use numerical simulation to study the seismic response of the complex system in recent years. Therefore, the research in this field still lacks the verification of the shaking table test, especially considering the seismic response from the elastic stage to the plastic stage [45]. Under the current background, this paper designs a scaled model of a tunnel-soil-surface structure system, obtains the acceleration of soil, the acceleration and strain of the tunnel and surface structure, and the interlayer displacement angle of the surface structure by inputting seismic waves of different intensities, and studies the dynamic response laws of the soil, tunnel, and superstructure. The research results of this paper have a certain significance for a reasonable understanding of the seismic response of the structure and provide a reference for the seismic design of the actual tunnel-soil-surface structure system.

2. Shaking Table Test

2.1. Shaking Table. The test was conducted in the laboratory of Civil Engineering, Hebei University of Engineering. The equipment is a unidirectional horizontal electrohydraulic servo-seismic simulation shaking table. More details regarding the performance parameters of the shaking table are shown in Table 1.

2.2. Design of the Similarity Ratio. This test adopted the artificial quality model. When calculating the similarity relation of the model, the geometric similarity ratio of the structure should be determined according to the actual test conditions, such as the size and bearing capacity of the shaking table, the actual influence range when considering the soil-structure interaction, and convenience of model manufacturing. In this test, the geometric similarity ratio was taken as 1:30. Then, the similarity relations of other dimensions were deduced from the basic dimensions of density, geometric length, and elastic modulus. The specific similarity relations are shown in Table 2.

2.3. Material and Design of the Model. The experiment mainly studied the whole process of the seismic response of the interaction system. Therefore, the microconcrete and galvanized wire were applied to simulate the prototype concrete and the reinforcement, respectively. The mix ratio of the model concrete was determined to be cement (#425): coarse sand: lime = 1:6:1:0.6. The mechanical properties of microconcrete were tested before building the model, in which the compressive strength and elastic modulus of microconcrete were 6.27 MPa and 8515 MPa, respectively. The measured similarity ratio of the elastic modulus was 1/3.6, which approximately satisfied the designed similarity ratio (1/4) of the elastic modulus. The prototype of the surface building was a 10-floor frame structure ($H_1 = 30$ m) with a pile foundation that was composed of 5 piles 12 m (L) in length. On the side of the superstructure ($s = 3$ m) were two parallel tunnels with an embedment depth of 6 m ($h_1$) for the shallow tunnel, and the distance between the soil surface and the top of the deep tunnel was 19.2 m ($H_2$). Table 3 shows the dimensions of the prototype and model.
system. Figure 1 shows the position relationship of each part of the prototype system. Figure 2 presents the model of the superstructure, pile foundation, and tunnel.

The remolded soil of a station construction site was selected as the model soil, which was sieved before the test. When preparing the model soil, the soil was placed into the model box layer by layer and was spread evenly. Each layer is controlled at a height of approximately 10 cm and was compacted to guarantee a consistent material density. The model soil was allowed to stand in the model box for 24 h in its natural state to simulate the natural consolidation process of the soil. After the remolded soil is sampled by the cutting ring method, the compression modulus was measured by the lateral compression test, and the cohesion and internal friction angle were obtained by the undrained consolidation test. The material properties of the model soil are listed in Table 4.

2.4. Model Container Design and Boundary Condition.

The supporting frame of the rigid model box in this test was composed of equilateral angle steel, the outer side perpendicular to the vibration direction was ribbed with oblique angle steel, and the bottom plate with a thickness of 10 mm was fixed with the shaking table by reserved bolt holes. In addition, the inner wall of the box was supported by 15 mm wooden boards. In order to simulate the deformation and elastic restoring force of soil in semi-infinite domain as much as possible and eliminate the influence of boundary effect, the polystyrene foam plastic...
board with a thickness of 100 mm and a density of 15 kg/m³ was set on the inner wall perpendicular to the horizontal vibration direction. The foam board has the best compression performance, and it is always in a linear elastic state during the test loading process. To prevent the relative slip between the model soil and the steel plate during excitation, a layer of gravel was placed at the bottom of the model box to increase the friction resistance on the contact surface. The design of the model box is shown in Figure 3(a).
Considering the geometric similarity ratio of the test, the model container dimensions were 2 m (longitudinal) × 1.5 m (transverse) × 1.4 m (height) (excluding the lower steel plate size), as shown in Figure 3(b). After the model box was made, it was verified that the boundary effect of the model container was reasonable by analyzing the acceleration of the soil at different positions [46].

2.5. Instrumentation. The main purpose of the test was to discuss the seismic response law of the tunnel-soil-adjacent structure system. Based on this, measuring points were arranged in different parts of the soil, tunnel, and superstructure to record the dynamic response of the system. The sensors used in the experiment include a CF0410-3X capacitive accelerometer (A) and strain gauge (S). The arrangement of sensors is shown in Figure 4.

The system consisted of 22 accelerometers and 28 strain gauges. To consider the propagation law of seismic waves in a different area, accelerometers A1-A6 and A7, A9, and A11-A13 were compared. Accelerometers A8 and A10 were set to compare the seismic response of tunnels. A14-A16 and A17-A22 were laid to monitor the seismic response of the surface structure and pile foundation, respectively. Strain gauges S1–S6 were mounted on the outer side of the column to obtain the microstrain. S7–S9 and S10–S12 were placed as a comparison to record the strain of the side and central pile, respectively. S13–S20 and S21–S28 were fixed on the outer faces of the shallow tunnel and deep tunnel to measure the strain of key areas of tunnels, respectively. Considering the limitation of the number of holes in the data acquisition instrument, only the main observation section was set up in the tunnel.

2.6. Loading Method and Test Cases. The test selected three different ground motions: Taft wave, LWD wave, and Tianjin wave. LWD wave, also known as Northridge wave, was recorded at Lake Wood Del Amo station during the Northridge earthquake in California on January 17, 1994. The acceleration time history and Fourier spectra of the input motions were shown in Figure 5, in which the predominant frequencies of Tianjin wave, Taft wave, and LWD wave are 0.9 Hz, 3 Hz, and 1.3 Hz, respectively. Based on the main measurement information, a “multistage” loading method was adopted during the test. Before each test, the model soil was compacted with a white noise excitation of 0.07 g and no less than 30 s. The shaking table should be suspended for 2–3 minutes between the last and the next test. The input wave was a horizontal excitation along the length of the model container, the original time interval was 0.02 s, and the time similarity ratio was 0.183, so the test time interval was 0.00366 s. The test cases were given in Table 5.

### Table 4: Parameters of model soil.

| Material          | Compression modulus (MPa) | Density (g/cm³) | Soil moisture (%) | Plastic limit (PL) | Liquid limit (LL) | Cohesive strength (kPa) | Friction angle (%) |
|-------------------|---------------------------|-----------------|-------------------|--------------------|------------------|------------------------|------------------|
| Model soil        | 8                         | 1.734           | 16.9              | 16.2               | 28.4             | 17.3                   | 25.6             |

3. Test Results and Interpretation

3.1. Acceleration Response of the Model Soil. To study the seismic response of soil in a tunnel-soil-surface structure system, the model soil is divided into two areas. The area along the tunnel axis and close to the surface structure is the central area (CA), while the area on the left side of the tunnel and away from the surface structure is taken as the far-field (FF) area. Accelerometers are arranged along the soil depth in the above two areas. Figure 6 shows the acceleration response of soil in the FF area during different seismic waves. Figure 7 shows the acceleration amplification response of soil in two regions under different test cases.

As shown in Figure 6, when the same seismic wave is input, the waveforms of A1 at the bottom and A5 at the surface of the model soil are basically the same except for the difference in peak acceleration. The acceleration response of soil under Tianjin wave is larger than that under Taft wave and LWD wave, which indicates that the seismic response of soil is related to seismic waves with different spectral components. After processing the seismic waves according...
to the experimental similarity ratio, the energy of the Tianjin wave is concentrated in 0–15 Hz, the Taft wave is concentrated at 3–30 Hz, and the LWD wave is concentrated at 2–25 Hz. In the spectrum of seismic waves, the energy of the Tianjin wave is relatively concentrated, and the energy distributions of LWD and Taft are scattered.

To investigate the difference in acceleration between the two regions of soil, the acceleration amplification factor is
introduced in this paper. The acceleration amplification factor is the ratio of the maximum absolute acceleration at the measured point to the maximum absolute acceleration of the input motion. Figure 7(a) shows that the peak acceleration in the two regions shows an increasing trend from the bottom to the top of the model soil except for A6 and A13, but the amplification factors in the two regions are different. The sudden decrease in the acceleration at the surface of the model soil is due to the overburden thickness at A6 and A13 being relatively thin (3 cm) and the compaction and stiffness being weak.

Specifically, the acceleration amplification coefficients of A11, A12, and A13 are all larger than those of A4, A5, and A6 in the FF area with the same burial depth, which indicates that the soil response in the CA is larger. The probable reason is that A11, A12, and A13 are affected not only by the tunnel but also by the surface structure-piles system on the right side of the tunnel. When the seismic wave is transmitted to the surface structure along with the soil, the inertial action of the superstructure acts on the soil again like a new source, resulting in the acceleration response of the soil near the tunnel-surface structure.
being stronger than that of the soil far away from the interaction area [34]. In Figure 7(a), the acceleration amplification factors of A7 and A9 near the deep tunnel are less than those of A1 and A3 at the same burial depth, indicating that the vibration of the tunnel affects the response of the surrounding soil, and the reflection and refraction of seismic waves at the interface between structures and soil lead to the change in the soil dynamic response. In general, the acceleration amplification factor of the FF area is smaller than that of the CA, and the acceleration response of the FF area has an obvious fluctuation in longitudinal development, which indicates that the nonlinear characteristics of the FF soil are stronger than those of the central soil. It also shows that the soil around the tunnel-surface structure system has better stiffness and stability.

To explain the change in the acceleration response of soil under the action of ground motion with different amplitudes, Figure 7(b) shows the peak acceleration amplification factors of the model soil under Tianjin wave with different intensities. As shown in Figure 7(b), the acceleration amplification factor of the soil gradually decreases with the increase of acceleration. Taking A5 as the research object, when Tianjin waves with amplitudes of 0.1 g, 0.2 g, 0.3 g, and 0.4 g are input, the acceleration amplification coefficients of soil at A5 are 1.902, 1.538, 1.379, and 1.078, respectively. This result indicates that when the earthquake intensity is small, the soil is in an elastic state and has a strong ability to transmit seismic energy. With the increase of ground amplitude, the model soil gradually exhibits elastoplasticity, and the increase in deformation, damping, and nonlinear properties leads to the enhancement of the energy dissipation capacity of the soil.

Figure 7(c) presents the peak acceleration amplification factor of soil in the far-field under the action of different seismic waves. For seismic waves with an amplitude of 0.1 g, the acceleration response caused by the Tianjin wave is larger than that caused by the LWD wave and Taft wave. This shows that the seismic response of the model soil is more sensitive to the input waves with richer low-frequency components.

3.2. Seismic Response of the Model Tunnel
3.2.1. Acceleration Response of the Model Tunnel. In the test, A10 and A8 are set in shallow and deep tunnels, respectively, to measure the acceleration response of tunnels. Figure 8 shows the acceleration amplification factor of tunnels under different test cases. It can be seen from Figure 8(a) that the acceleration response of the shallow tunnel is greater than that of the deep tunnel. Moreover, the acceleration amplification coefficients of the shallow tunnel and the deep tunnel decrease with the increase of the input acceleration. The reason is that the softening of the model soil and the stiffness degradation of the model tunnel are more sensitive to input motion with higher amplitude. The seismic responses of A8 and A10 under different ground motions are presented in Figure 8(b). In Figure 8(b), the peak acceleration of the tunnel induced by the Tianjin wave is greater than that induced by the LWD and Taft waves. This result is consistent with the law of seismic response of soil under different seismic waves in Section 3.1. This is because the tunnels are restrained by the surrounding soil and show the same dynamic characteristics as the model soil.

3.2.2. Strain Response of the Model Tunnel. Shallow and deep tunnels are divided into five key parts along the circumference, namely, vault, spandrel, hance, arch springing, and invert. The layout of strain gauges is shown in Figure 4.

As presented in Figure 9, the strain time history in different parts of the tunnel is roughly the same, but the peak strain values are different. The strain values of S20 do not return to the original value after the test stops, which indicates that the soil around the tunnel exhibits permanent strain after vibration, and the strain of the model soil causes additional strain to the tunnels.

Figure 10 shows that the peak strains of the shallow tunnel and deep tunnel are clearly different under the action of the Tianjin wave. The peak strain of shallow and deep tunnels increases with increasing input acceleration, which indicates that the deformation of tunnels is more obvious with the increase of vibration intensity. During earthquakes, for the five key parts of the deep tunnel, the peak strain of the

| Test no. | Excitation waveform | Peak acceleration (g) | Intensity |
|----------|---------------------|-----------------------|-----------|
| W-1      | White noise         | 0.07                  |           |
| LWD-1    | LWD                 | 0.1                   |           |
| Taft-1   | Taft                | 0.1                   |           |
| Tj-1     | Tianjin            | 0.1                   |           |
| W-2      | White noise         | 0.07                  |           |
| LWD-2    | LWD                 | 0.2                   |           |
| Taft-2   | Taft                | 0.2                   |           |
| Tj-2     | Tianjin            | 0.2                   |           |
| W-3      | White noise         | 0.07                  |           |

| Test no. | Excitation waveform | Peak acceleration (g) | Intensity |
|----------|---------------------|-----------------------|-----------|
| LWD-3    | LWD                 | 0.3                   | 7-Degree (moderate earthquake) |
| Taft-3   | Taft                | 0.3                   |           |
| Tj-3     | Tianjin            | 0.3                   |           |
| W-4      | White noise         | 0.07                  |           |
| LWD-4    | LWD                 | 0.4                   |           |
| Taft-4   | Taft                | 0.4                   |           |
| Tj-4     | Tianjin            | 0.4                   |           |
| W-5      | White noise         | 0.07                  |           |

8-Degree (moderate earthquake)
spandrel and spring is larger, while the peak strain of the hance and spring of the shallow tunnel is larger than that of other parts. According to previous research, the maximum value appears in the region of 45° between the two sides of the lining and the vertical symmetry axis, i.e., the "X" region of the section. However, different consequences are presented for a shallow tunnel. Considering the location of the two tunnels, the reason can be that the shallow tunnel is close

Figure 6: Acceleration time history of model soil.
Figure 7: Acceleration amplification factor along the soil depth during ground motions. (a) Soil in different areas under the Tianjin wave. (b) Soil in far-field areas under Tianjin wave. (c) Soil in far-field areas under different seismic waves.

Figure 8: Acceleration amplification factor of the tunnels. (a) Tunnels under Tianjin wave. (b) Tunnels under different seismic waves.
to the surface structure, leading to a strain response that is different from that of the deep tunnel.

Table 6 shows the strain response of the deep tunnel at S24 under different seismic waves. The peak strain at S24 under the action of the Tianjin wave with an amplitude of 0.1 g is 1.19 times that under the action of the LWD wave. When the peak acceleration is 0.4 g, the peak strain at S24 during the Tianjin wave is 1.47 times that during the LWD wave. The results show that when the input ground motion is close to the predominant frequency of the site, the deformation response of the tunnel clearly increases. With the increase of the ground motion intensity, the difference in the strain response under different waves becomes increasing larger.

3.3. Seismic Response of the Model Surface Structure-Piles System

3.3.1. Acceleration Response of the Model Surface Structure-Piles System. In order to study the acceleration response of the surface structure-pile system in the presence of a tunnel,
A17-A22 are arranged on the 2nd, 4th, 6th, 8th, 9th, and 10th floors of the surface structure, and A14-A16 are arranged at equal intervals from the top to the bottom of the middle pile. Figure 11 presents the acceleration time history of the surface structure-pile system under the action of the Tianjin wave when the peak acceleration is 0.1 g. To describe the variation in acceleration with the height of the system, Figure 12 shows the variation characteristics of the peak acceleration of the surface structure-piles with the height of the model system under various test cases.

In Figure 11, the acceleration time history of each measuring point in the model system during the earthquake is similar to that of the input ground motion.

Figure 12(a) provides the acceleration amplification factor of the surface structure-piles system. For the surface structure, the distribution of the acceleration amplification factors has an 'S' shape along the height of the structure, and the acceleration of the top layer is the largest, but the bending point appears on the 8th floor. This is related to the natural vibration characteristics of the structure. The response of the structure is the combination of its modal responses, but the contribution of each mode is different. If a certain mode of the structure resonates with the seismic wave filtered by the soil, then the modal response will be amplified, and the response quantity at different heights will be different. Under the Tianjin wave, when the peak acceleration is small, the peak acceleration amplification factors of the structure are large. With increasing acceleration, the amplification factors decrease, but the values are still greater than 1. This series of data implies that when the input motion is at low amplitude, the soil and the surface structure are in an elastic state and sensitive to seismic waves. With the increase of vibration times and intensity, the nonlinear and softening behavior of the model soil is strengthened, and the ability to transmit vibration is reduced. Moreover, different degrees of damage appear in the structure, which leads to a weakening of the seismic response of the surface building. Additionally, it is worth noting that the amplification factors of the structure are larger than those of the model soil. This result is caused by the relative stiffness of the tunnel and soil. For pile foundation, the peak acceleration at the top of the pile is greater than that at the middle and bottom. This is because the top of the pile is constrained by the pile cap and integrated with the surface structure, while the middle and bottom of the pile are constrained by the soil. The stiffness of the structure and the cap is superior to that of the soil, and the inertia of the surface structure under earthquakes is large, resulting in the response of the structure being stronger than that of the soil during an earthquake. Therefore, the peak acceleration at the top of the pile affected by the superstructure is greater than that at other parts of the pile. With the increase of the input acceleration, the amplification factors decrease due to the nonlinearity of the pile and the soil.

As presented in Figure 12(b), when inputting different ground motions, the response of the surface structure-pile system is different. The acceleration response of the system under the excitation of the Tianjin wave is larger than that under the excitation of the Taft wave and LWD wave.

3.3.2. Displacement Response of the Model Surface Structure-Piles System. Due to the limitation of the test conditions, only accelerometers are arranged instead of displacement meters. By filtering the acceleration time history, the speed and displacement time history of the model structure can be obtained by integral transformation, and the interlayer displacement angle can be further obtained. Figure 13 shows the variation in floor displacement and interlayer displacement angle with the height of the surface structure under different test cases.

Figure 13(a) shows the displacement envelope diagram of the surface structure, and the displacement is the absolute displacement of the model structure. From the distribution of the maximum floor displacement, it can be seen that the deformation of the surface structure under horizontal earthquakes is mainly shear deformation. In Figure 13(a), the floor displacement increases with increasing seismic intensity. The main reason is that with the increase of the input acceleration, the cracks in the structure develop further, the degree of entering plasticity increases, and the stiffness of the structure decreases, which eventually leads to a continuous increase in the floor displacement.

Figure 13(b) shows the interlayer displacement angle of the surface structure during an earthquake. In Figure 13(b), under the action of Tianjin waves of 0.1 g and
the interlayer displacement angle increases first and then decreases along the height, and the interlayer displacement angle of the 4th layer is the largest. When the amplitude is 0.3 g and 0.4 g, the interlayer displacement angle decreases along the height, and the interlayer displacement angle of the 2nd layer is the largest. Moreover, when the input peak acceleration increases from 0.1 g to 0.4 g, the interlayer displacement angle also increases. It can be seen from the above results that the displacement response of the structure is different under earthquakes of various intensities, and the position of the maximum interlayer displacement angle is also different. With increasing input peak acceleration, the weak layer of the surface structure moves down, and the interlayer displacement angle of the middle and lower layers is significantly larger than that of the upper layers, indicating that the structure has a large plastic deformation under rare earthquakes.

Figure 13(c) shows that when the same peak acceleration is input, the interlayer displacement angle of the structure
during the Tianjin wave is the largest. This is consistent with the acceleration response law of the surface structure under different seismic waves.

To study the destructive state of the surface structure during the Tianjin wave, the displacement angle distribution between the layers is compared with the limits of intact (1/550), minor damage (1/250), moderate damage (1/120), and serious damage (1/50) specified in the GB50011-2010 Code for Seismic Design of Buildings.

In Figure 13(b), when a Tianjin wave with an amplitude of 0.1g is input, the interlayer displacement angles below the 6th floor are less than 1/250, and the values of the 8th-10th floors are less than 1/550, indicating that the structure is minor damage. When the amplitude is 0.2g, the interlayer displacement angles between the 6th floor are between 1/120 and 1/250, which suggests moderate damage; the interlayer displacement angles of the 8th-9th floors are between 1/550 and 1/250, which means minor damage; and the value of the 10th floor is less than 1/550, which means that this floor is intact. When the amplitude is 0.3g, the displacement angles between floors below the 4th floor are between 1/50 and 1/120, which suggests serious damage; the 6th-8th floors exhibit moderate damage, and the remainder of the floors demonstrate minor damage. When the peak acceleration is 0.4g, the floors below the 2nd floor are completely destroyed, and the 4th-6th floors are seriously damaged. The results show that the surface structure meets the repair performance target under moderate earthquakes and does not collapse under rare earthquakes.

### 3.3.3. Strain Response of the Model Surface Structure-Piles System

During the test, strain gauges are arranged in frame columns and piles to measure the dynamic strain response.

Figure 14 shows envelope diagrams of the strain of the surface structure-piles system along the height.

In Figure 14(a), when Tianjin waves with different intensities are input, the strain of the surface structure-pile increases with increasing peak acceleration. Under the action of seismic waves with the same intensity, the strain response of the pile foundation is clearly less than that of the surface structure. At the same time, from the strain responses at different heights of the surface structure, it can be seen that the strain of the frame column decreases gradually with the increase of the number of floors, and the strain in the bottom floor is the largest.

Cracks do not occur immediately when the principal tensile stress reaches the tensile strength of concrete, but concrete will appear to crack when the tensile strain reaches the ultimate tensile strain. The ultimate tensile strain of concrete is 150 με. The strain response of the surface structure-pile system under the action of Tianjin waves with amplitudes of 0.1g and 0.4g is taken as an example. When the amplitude is 0.1g, the strain of the frame columns is less than 150 με, and the results show that there is no obvious crack in the frame column. When the amplitude is 0.4g, the strain of all measuring points except S12 exceeds 150 με, indicating that cracks occur in the frame columns and piles of the whole system. In particular, the strain of frame columns on the 2nd-6th layers exceeds 300 με. When the peak acceleration increases from 0.1g to 0.4g, cracks in the surface structure gradually appear from the bottom to the top, and cracks in the bottom develop rapidly. Combined with the interlayer displacement angle of the 2nd layer, the members below the 2nd layer are seriously damaged and even have the risk of collapse.

In Figure 14(b), consistent with the response law of acceleration and displacement of the surface structure-pile...
system during ground motions, the strain of the system under the Tianjin wave is large.

3.4. Experimental Phenomenon. The macroscopic phenomena observed in the test are mainly as follows. (1) When the peak acceleration of the input is small, the swing of the model container and soil are slight, and the vibration of the surface structure is also not obvious. With increasing input acceleration, the seismic response of the soil and surface structure increases. (2) The seismic response of the soil and structure is the strongest when the Tianjin wave is input. During a moderate earthquake with a seismic fortification intensity of 7°, slight horizontal cracks appear at the ends of the beams of the 1st-5th layers. Under the rare earthquake of 7°, cracks of the 1st-5th layers develop further, and most cracks at the beam end penetrate the cross-section. In addition, new microcracks appear in the 8th-9th layer. Under the action of the moderate earthquake of 8°, the length and number of cracks at the column and beam ends have increased, the column bottom of the first layer has cracked, and the surface concrete at the column ends has fallen off. During the rare earthquake of 8°, the cracks at the ends of the beams above the 7th layer develop rapidly, and most frame beams below the 5th layers are seriously damaged. Moreover, the surface structure is inclined greatly (Figure 15). From the above test phenomena, the surface structure in the tunnel-soil-surface structure system can continue to be used without repair in the case of a moderate earthquake of 7°. The structure can also continue to be used through general repair or overhaul after a rare earthquake of 7° and a magnitude earthquake of 8°. The structure will not collapse in the case of a rare earthquake of 8°. The above results meet the seismic fortification standard of China, and the structure demonstrates good seismic performance.

4. Conclusions

In this paper, a shaking table test was carried out on the seismic response law of the tunnel-soil-surface structure interaction system subjected to various types of seismic loading; the seismic response of the tunnel and the surface structure and the influence of the interaction system on the dynamic response of the surrounding soil were studied. The key findings of this study were achieved as follows:

(1) The acceleration response of soil near the tunnel-surface structure system is greater than that of soil far away from the interaction area. It indicates that the tunnel-surface structure interaction system has a certain influence on the seismic response of surrounding soil. With the increase of the input peak acceleration, the mechanical properties of the model soil have changed greatly, and the acceleration amplification effect at different depths is attenuated to some extent.

(2) The acceleration response of the shallow tunnel is greater than that of the deep tunnel, and the tunnel is more sensitive to seismic waves with rich low-frequency components. These results are consistent with the seismic response law of the soil and verify that the seismic response of the tunnel is related to the dynamic characteristics of the model soil.

(3) For the deep tunnel, the maximum strain appears in the region of 45° between the two sides of the lining and the vertical symmetry axis (i.e., spandrel and spring). However, for the shallow tunnel, the different consequence is that the peak strain of the hance and spring is larger than that of other parts. The reason for this phenomenon is that the existence of the surface structure changes the deformation of the tunnel. Therefore, it is necessary to pay attention to these parts in the seismic design of tunnels in the presence of the surface structure.

(4) For the surface structure, the acceleration amplification factor is distributed in an "S" shape along the height. As the acceleration increases, the acceleration amplification factor decreases, but it is still greater than 1. However, it should be noted that the amplification factor of the structure is greater than that of the model soil. This result is a consequence of the soil and structure relative stiffness. In terms of the pile foundation, the peak acceleration at the top of the pile is greater than that at the middle and bottom of the pile, indicating that the earthquake damage of the pile foundation generally occurs on the top of the pile. This is consistent with the survey results of previous earthquake disasters.

(5) When a tunnel exists, the floor displacement of the surface structure increases with the increase in earthquake intensity, and the deformation under horizontal earthquakes is mainly shear deformation. According to the damage characteristics of the surface structure under different seismic intensities, the structure can meet the seismic requirements of “repairable in moderate earthquakes and not fail in rare earthquakes”.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.
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