Research Article

Analysis of Shaking Table Tests of Underground Structures considering the Influence of the Structure-Soil Interface

Feng Shuang Guo [1,2] **Yun Sheng Wang** [1] **Chang Bao Wang** [3] **and LiJuan Wang** [1,2]

[1]*State Key Laboratory of Geohazard Prevention and Geoenvironment Protection, Chengdu University of Technology, Chengdu 610059, China*
[2]*Sichuan Aerospace Vocational College, Chengdu 610100, China*
[3]*Sichuan Institute of Geological Engineering Investigation Group Co. Ltd, Chengdu 610000, China*

Correspondence should be addressed to Feng Shuang Guo; 2578010085@qq.com

To investigate the seismic performance of underground structures under the action of the structure-soil interface, in this study, experiments were performed using plexiglass structures (two pieces) and a concrete structure (one piece) as the research objects. The surface of one plexiglass structure was prepainted with a layer of cement mortar as the contact surface between the structure and soil, and the other plexiglass structure was not treated and used for comparison. A rigid model box measuring $2.25\,m \times 2.25\,m \times 1.5\,m$ was placed on a $3\,m \times 3\,m$ shaking table, and the box was filled with the configured model soil and the underground structure prepared in advance. Input transverse uniform excitation was imparted to the whole system. A shaking table model test was performed on the underground structures to analyse the acceleration response, stress strain, and earth pressure changes in the underground structure, and the influence of the contact surface on the seismic dynamics of the underground structure was evaluated. The test results showed that under uniform excitation, the dynamic characteristics of the underground structures were greatly affected by the intensity and depth of the seismic waves. (1) When the soil-structure contact was considered, the stress and strain of the structures increased significantly, and the stress-strain value was significantly greater than the stress-strain value of the soil-structure interface in a fully bonded state. (2) There were inconsistencies between the acceleration peak curve of the plexiglass structure considering the contact effect and the acceleration peak curve of the plexiglass structure without considering the contact effect. The difference between the two lies mainly in the corresponding maximum peak acceleration and the Fourier spectrum amplitude. With respect to the value and frequency composition, regardless of whether the input acceleration intensity was 0.2 g or 0.5 g, the peak acceleration of the organic structure was greater when the contact surface effect was considered than without the contact surface effect. Therefore, the structure-soil interface needs to be considered in actual engineering. The presence of the contact surface improves the safety of the structure and is helpful for seismic design. The results of this study provide a basis for further research on the influence of soil-pipe contact on the seismic response of underground structures.

1. Introduction

Underground structures are an indispensable infrastructure for municipal construction and convenience in daily life. Accordingly, many refer to such structures as "lifeline projects." Underground structures are built later than buildings on the ground and are buried, which limits people's understanding of these structures. Researchers long thought that underground structures are constrained by the surrounding soil and undergo relatively small deformation, even when threatened by an earthquake. Consequently, the seismic effects of underground structures have been considered superior to those of above

ground buildings, and insufficient attention has been paid to seismic research on underground structures.

The 1995 Osaka-Kobe earthquake in Japan challenged these notions and was a major event that cannot be ignored in the history of seismic research on underground structures. The earthquake caused the collapse of subway stations and multiple ground collapses, demonstrating that underground structures are not as strong as previously imagined. This destruction attracted the attention of the engineering community, and since then, researchers have focused on the earthquake resistance of urban underground structures.

Research studies on the seismic performance of underground structures had increased in the aftermath of the Osaka-Kobe earthquake [1–6]. Research methods for underground structures include theoretical analyses, site surveys, numerical analyses, and simulation tests. In recent years, shaking table tests have become one of the most effective tools for seismic research on underground structures [7]. Chen et al. [8, 9], Jiang et al. [10, 11], Zuo et al. [12], and Han et al. [13] conducted a series of shaking table tests to analyse the seismic damage characteristics of underground structure s in liquefaction sites. Yan et al. [7, 14] and Yu [15] conducted a multipoint excitation shaking table test analysis on the long tunnel of the Hong Kong-Zhuhai-Macao Bridge and further proved that due to uneven excitation along the length, long structures may suffer more damage than that of short structures.

A prerequisite in most seismic analyses of underground structures is to assume that the structure and the soil pasted completely. Such studies assume that when subjected to an earthquake, the structure and the soil are subjected to the same force and do not consider the differences in the natures of the structure and the soil. In fact, soil and structures are different types of media, and the existence of the structure-soil interface can cause slip and separation deformation to occur between the two, which will greatly impact seismic calculations. To reduce the error generated in actual engineering, structure-soil interactions must be considered in the seismic dynamic responses of underground structures. Investigations of the Osaka-Kobe earthquake revealed separation and slippage between structures and the soil. These findings indicate that the strength of the contact between the two is low, leading to shear deformation and formation of a failure surface.

In addition, these studies do not consider the influence of structure-soil contact coupling on structure dynamics. Calculation results obtained in this way differ significantly from the actual situation.

In this study, shaking table tests were performed to analyse the coupling between the underground structure and the soil and to verify the existence of the contact surface which plays an important role in the seismic dynamic response of underground structures.

2. Test Design

2.1. Similitude Ratio Design. In the design of the shaking table test, the issue of similitude must be solved first. The similitude relations in this paper were obtained on the basis of the Buckingham-π theorem, which is widely used for the design of shaking table tests [14].

In the model test, the ratio of the corresponding physical quantity between the prototype and the physical model is defined as the similarity coefficient, which is represented by C_i (i is the corresponding parameter). The similitude ratio is shown in Table 1. Based on a similarity ratio between the prototype and the model of 5 : 1, it can be determined that the weight of the model soil in the test is 21 kN/m.^{3}

2.2. Model Pipe Surface Treatment. The most widely used structure materials in underground structure simulation tests are concrete, plexiglass, PVC, and steel. For repeatability and economic convenience, plexiglass was chosen as the pipe material in the present test.

The surface roughness of plexiglass is very different from that of concrete. Therefore, the plexiglass was pretreated before the tests by brushing a 2 mm thick layer of 2 : 1 cement mortar on the surface of the plexiglass.

The sand used for the cement mortar was Fujian standard sand. Its particle size grading curve is shown in Figure 1, and the equipment used in the configuration process is shown in Figure 2.

The researchers conducted a direct shear test on the plexiglass-sand interface (Figure 3). The results are shown in Figure 4.

Figure 4 shows that when different stresses (50 kPa, 100 kPa, 150 kPa, and 200 kPa) are applied, the direct shear test curve of the plexiglass-sand interface is more consistent with the direct shear test curve of concrete sand; that is, it is feasible to use plexiglass coated with cement mortar instead of common concrete to complete the shaking table simulation test of underground structures.

2.3. Shaking Table. A single shaking table (Figure 5(a)) with an active box filled with the model soil was used to conduct a series of single-point shaking table tests. The system parameters of the large-scale shaking table of the Structural Engineering Test Center of Hainan University are shown in Table 2.

2.4. Model Soil Box. The model box used in this experiment is a special rigid model box (Figures 5(b)–5(d)), which is welded with side angle steel to support the steel frame, and its plane shape is rectangular. The size of the model box is 2.25 m × 2.25 m × 1.5 m (the length along the vibration direction is 2.25 m, the length perpendicular to the vibration direction is 2.25 m, and the clear height is 1.5 m). A 40 mm thick polystyrene foam board is laid on the inner sidewall of the box to absorb seismic wave energy and reduce the reflection of the sidewall wave; a layer of plastic film is laid around the model box to prevent leakage of the test soil.

2.5. Seismic Wave Form. In this test, a representative El Centro wave (Figure 6) was selected as the input prototype wave, and a 5-level loading form (0.1 g, 0.2 g, 0.3 g, 0.4 g, and 0.5 g) was used. The excitation directions of all the working conditions were horizontal (X), and the loading conditions are shown in Table 3.

TABLE 1: Similitude ratio of model structure and model soil.

| Types	Physica quantity	Similitude relation	Model similitude ratio
Geometric properties	Length l	C_L	1/5
	Inertia moment I	$C_I = C_L{}^4$	1.5×10^{-4}
	Equivalent density ρ	C_ρ	1
Material properties	Flexural rigidity EI	$C_{EI} = C_L{}^5 \, C_\rho \, C_g$	0.3×10^{-3}
	Compressive rigidity EA	$C_{EA} = C_L{}^3 C_\rho C_g$	0.8×10^{-4}
	Gravity acceleration g	C_g	1
	Mass m	$C_m = C_\rho C_L{}^3$	0.8×10^{-4}
	Force F	$C_F = C_L{}^3 \, C_\rho \, C_g$	0.8×10^{-4}
Dynamic properties	Acceleration a	C_a	1
	Duration t	Ct	0.448
	Dynamic deformation r	$C r$	1/5
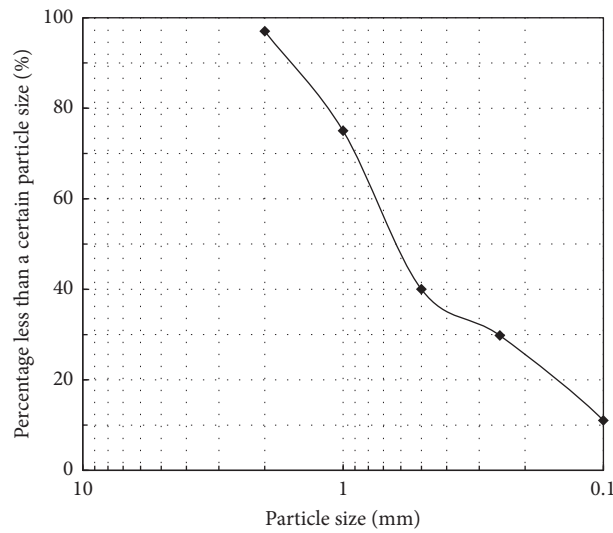
FIGURE 1: Grain size curve of Fujian standard sand.

2.6. Sensor Layout. Five accelerometers were arranged (A1, A2, A3, A4, and A5) at a certain distance on the outer wall of the structure to explore the change in the acceleration of the structure and arrange accelerometer A0 in the soil to monitor the acceleration of the soil (Figures 7–9). These sensors were all pasted on the surface of underground structures.

The strain gauge (S) is mainly used to measure the axial strain of the structure; the earth pressure gauge (P) can be used to monitor the change in the earth pressure on the contact surface. Figure 7 is a schematic diagram of the sensor layout, and Figure 8 shows a dynamic signal acquisition system. All the prepared underground structures in the model box are placed and covered with sand. When all the work was completed, the dynamic signal real-time acquisition system is turned on, experiments are conducted, and data are collected.

3. Results and Analysis

When the acceleration peak is small (0.1 g), there is no obvious change on the surface of the soil layer; when the input acceleration peak is 0.3 g, the sand will bounce, and the

box does not obviously shake; when the input acceleration peak is 0.5 g, the sand jumps more, the box begins to shake obviously, and a small displacement is observed.

3.1. Acceleration Time-History Spectrum. The acceleration response can be used to analyse the dynamic characteristics of underground structures under earthquake excitation.

Figure 10 shows the acceleration time-history curve and the corresponding Fourier spectrum of monitoring points A0 (soil accelerometer) and A4 (structure accelerometer) under earthquake excitation.

When a 0.2 g seismic excitation was input (Figures 10(a)–10(c)), the structure acceleration and the soil acceleration waveform (Figure 10(a)) were consistent, and the Fourier spectrum composition was also consistent with this input. At this time, the soil had a strong constraint on the structure, and the acceleration response of the structure was subject to the acceleration response of the soil. The responses were basically the same.

When a 0.5 g seismic excitation was input (Figures 10(d)–10(f))), the acceleration response of the structure was greater than that of the soil (Figure 10(d)). As

Figure 2: Materials and instruments used in the test: (a) Fujian standard sand for testing; (b) cement; (c) plexiglass sample after applying cement mortar; (d) soil analysis sieves with the apertures of 0.25 mm and 0.5 mm; (e) electronic scale.

shown in Figure 10(e), when the structure-soil contact was considered, there was obvious relative displacement between the structure and the soil, indicating that the structure was easier to deform, and the acceleration response of the structure was more obvious.

When the structure-soil contact surface was not considered, the structure's surface was fully integrated with the soil. There was a difference in the acceleration response waveform between the two, but it was not obvious, as shown in Figure 10(f).

Moreover, when considering the structure-soil contact, the Fourier spectrum of the structure acceleration had multiple peaks (Figure 11(a) and 11(c)), with more intermediate and low frequencies and richer components. By contrast, the Fourier spectrum component of the structure that did not consider the contact effect was less rich, and the spectrum component was relatively stable (Figures 11(b) and 11(d)).

In contrast, the structure considering the contact effect was more prone to structural deformation and failure.
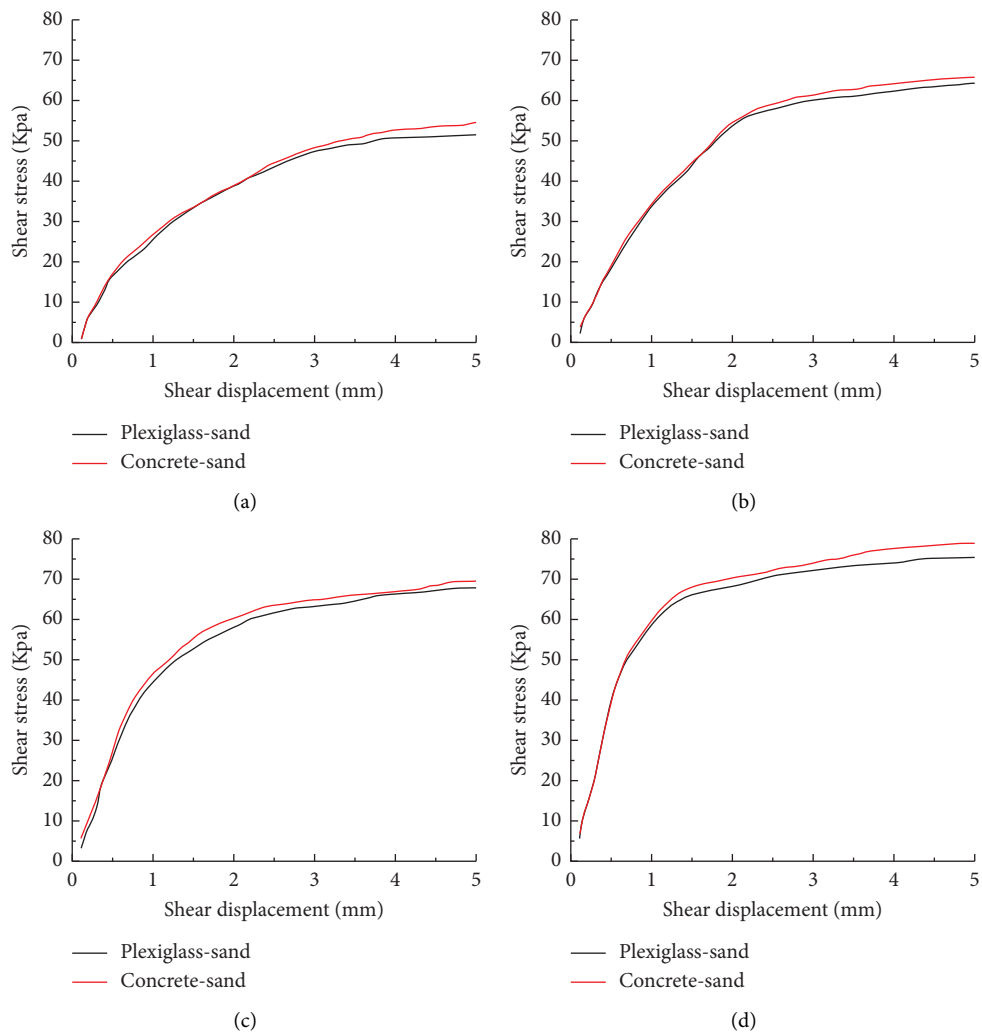
FIGURE 3: Direct shear test.

(a)

(b)

(c)

(d)

FIGURE 4: Direct shear test curves of the plexiglass-sand interface.

In addition, the following conclusions can be drawn: from bottom to top, the acceleration amplification coefficients at the three observation points show an increasing trend, which indicates that the structure vibration is stronger after the seismic wave is affected, and the upper structure reflects the most intense vibration (Table 4).

3.2. Axial Strain of the Structure. The strain energy of the structure reflects the deformation mode and force of the structure and is an important parameter in the design of underground structures [16].

The strain gauge was installed at the axis above the outer surface of the structure.
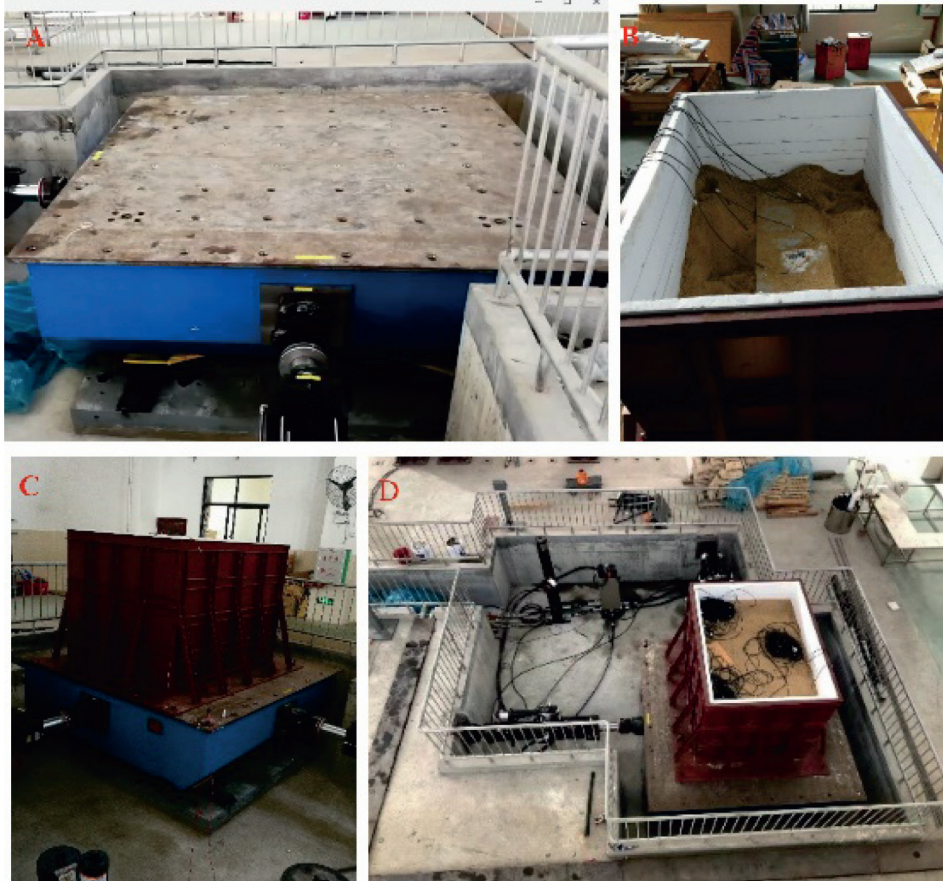
FIGURE 5: Rigid model box with built-in flexible material: (a) shaking table; (b) model box containing 40 mm thick polystyrene foam board on the inner wall; (c) shaking table with model box installed; (d) overall view of the shaking table.

TABLE 2: Performance parameters of the shaking table.

Parameter	Performance index
Table size (m × m)	3 × 3
Freedom of motion	2
Maximum bearing (t)	20
Maximum simple string vibration velocity (mm·s^{-1})	750
Maximum displacement of table (mm)	250 mm
Maximum seismic velocity (mm·s^{-1})	1000
Maximum overturning moment (t·m)	30
Maximum eccentric moment (t·m)	10
Operating frequency range (Hz)	0–50
Maximum acceleration of table with full load (g)	X: ±1.1; Y: ±1.1; Z: ±1.1

Figure 12 shows the strain time-history curve of the structure in a uniform field when the loading level is 0.5 g. The peak axial strain of the structure increases with the increase in the load level and reaches a maximum in the middle of the structure, with smaller values on both sides of the structure. When the structure-soil contact effect is considered, the peak value for the axial strain of the pipe is large because the contact surface increases the relative displacement between the structure and the soil, resulting in great structure deformation.

3.3. Structure Stress Response. With increasing earthquake intensity, the stress value corresponding to each point of the structure gradually increases.

The maximum principal stress value appears in the middle of the bottom of the pipe (point 2). Under the horizontal earthquake action of 0.1 g, 0.2 g, 0.3 g, 0.4 g, and 0.5 g, when the contact effect is considered, the maximum principal stress values of the bottom plate are 499.9 kPa, 927.8 kPa, 1327.5 kPa, 1571.7 kPa, and 1827.9 kPa, respectively. When the soil-pipe contact effect is not considered,
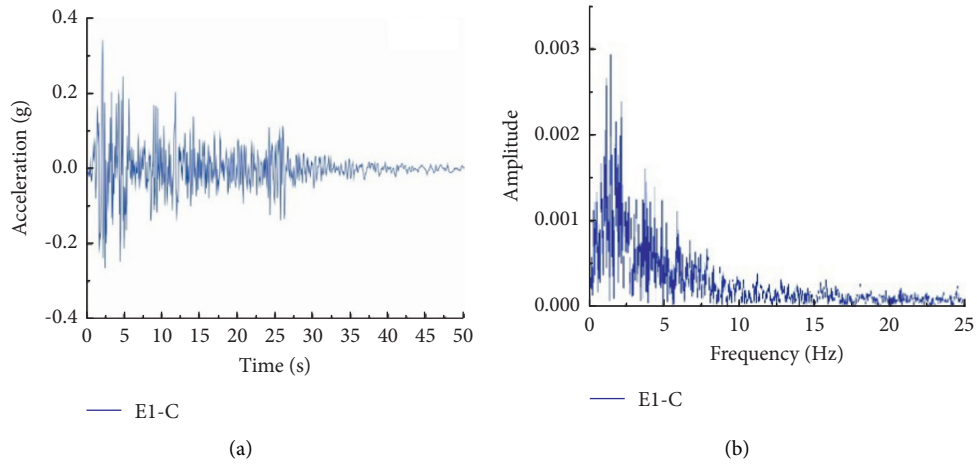
(a)

(b)

Figure 6: Acceleration time-history curve and Fourier spectrum of the representative E1 Centro wave.

Table 3: Shaking table model test conditions of underground structures.

Working condition	Seismic excitation wave	Incentive method	Peak acceleration (g)
1	E1 Centro wave	Unanimous	0.1
2	E1 Centro wave	Unanimous	0.2
3	E1 Centro wave	Unanimous	0.3
4	E1 Centro wave	Unanimous	0.4
5	E1 Centro wave	Unanimous	0.5
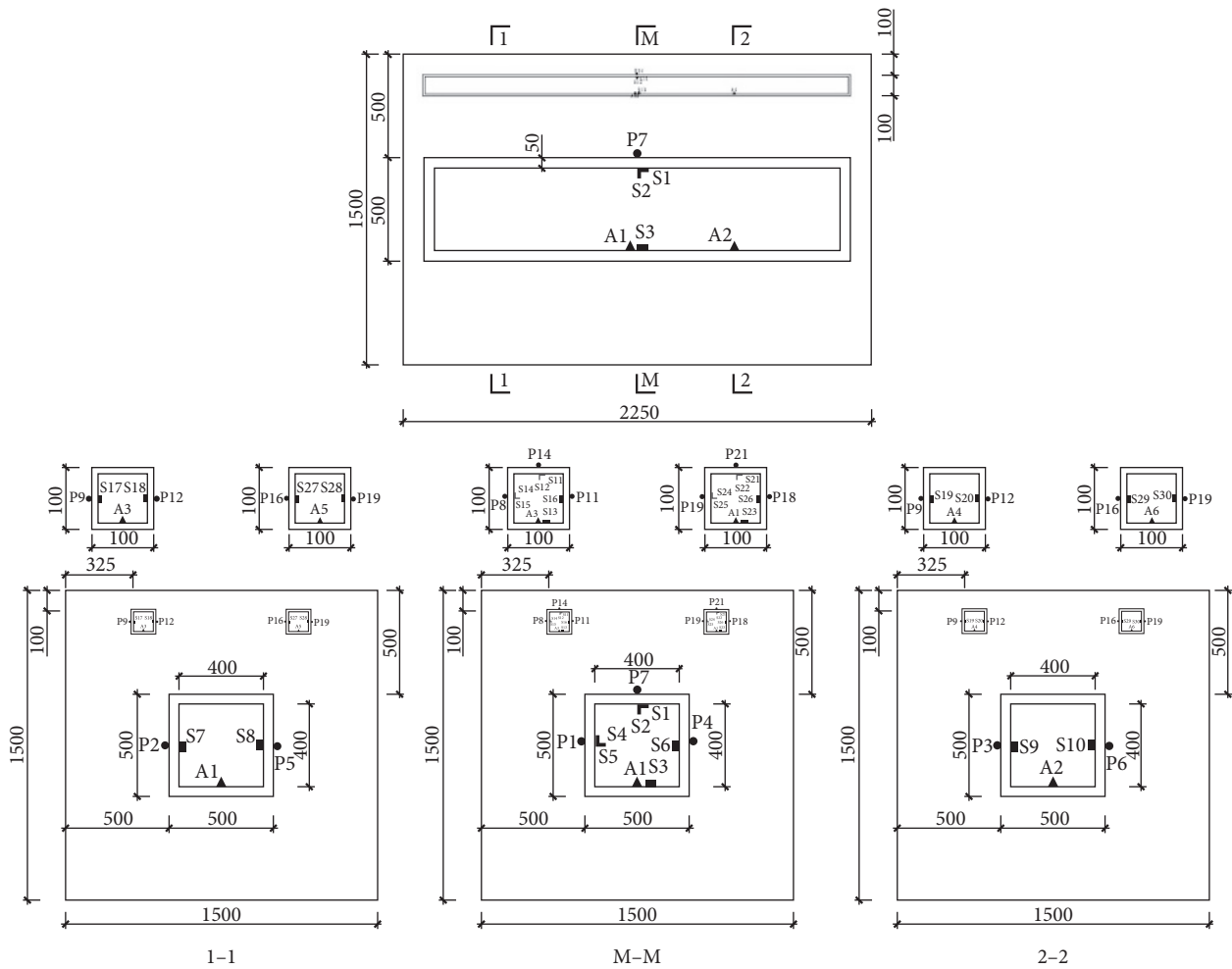
Figure 7: Conditions of sites and layout of sensors.
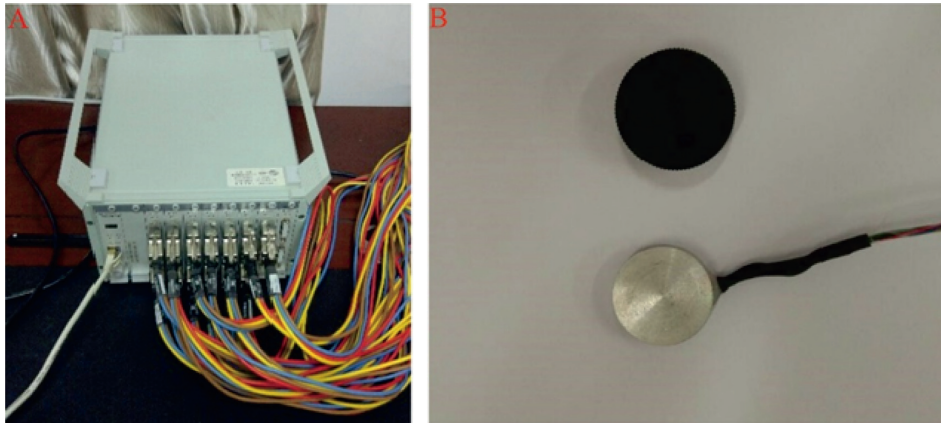
Figure 8: Dynamic signal real-time acquisition system: (a) data acquisition instrument; (b) earth pressure cell.
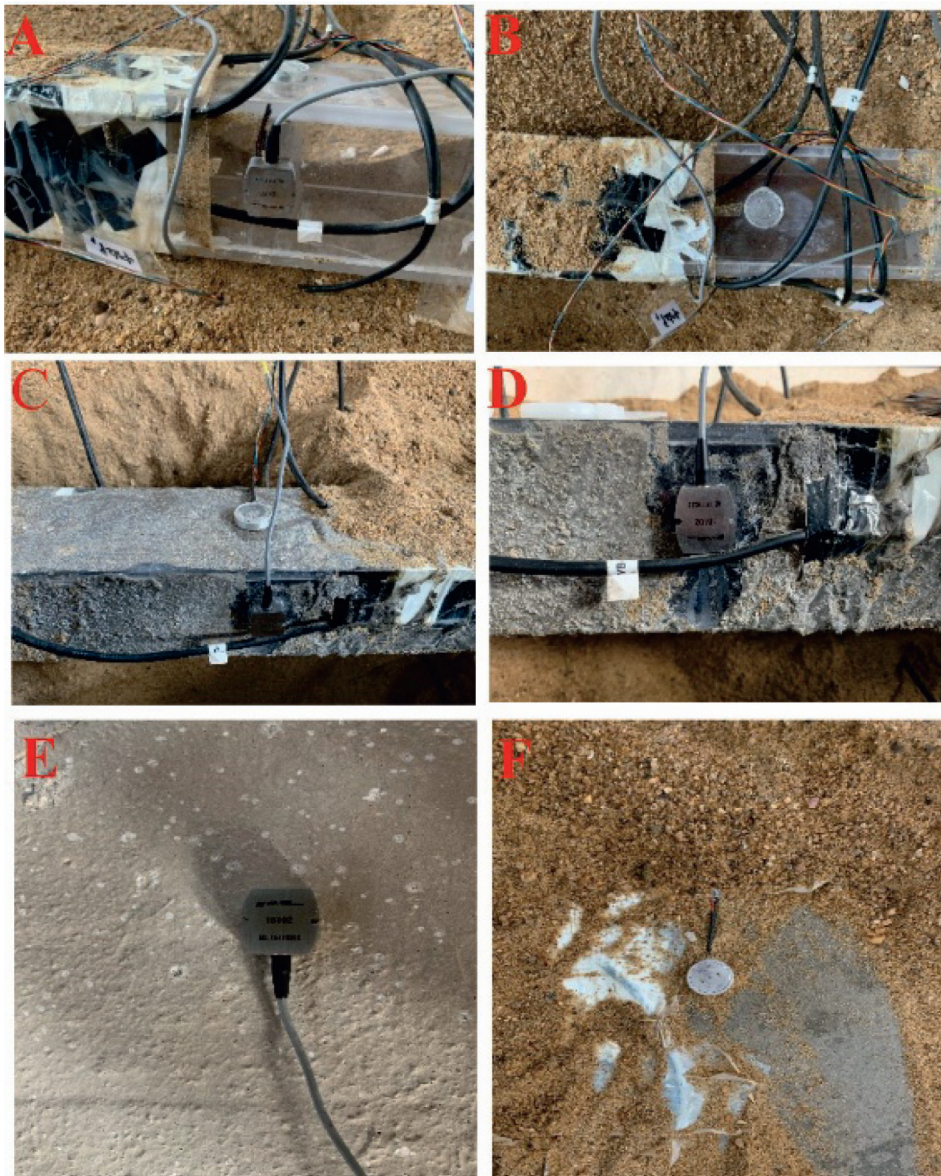

Figure 9: Underground structures after laying the test instrument.
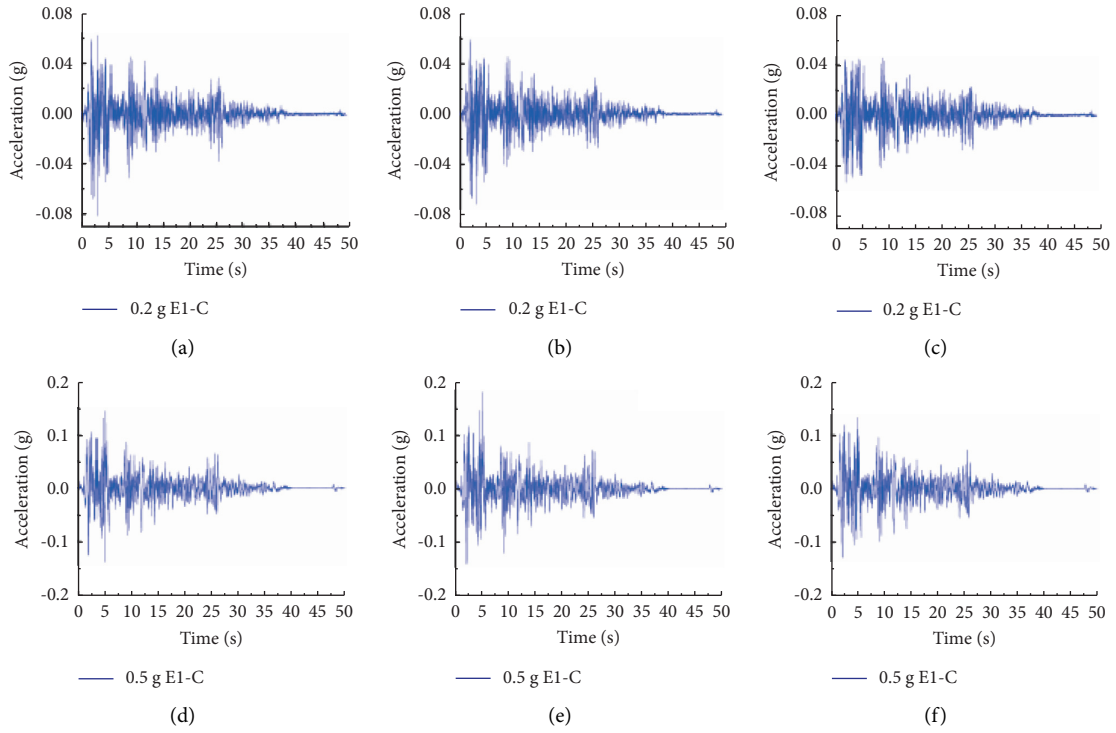
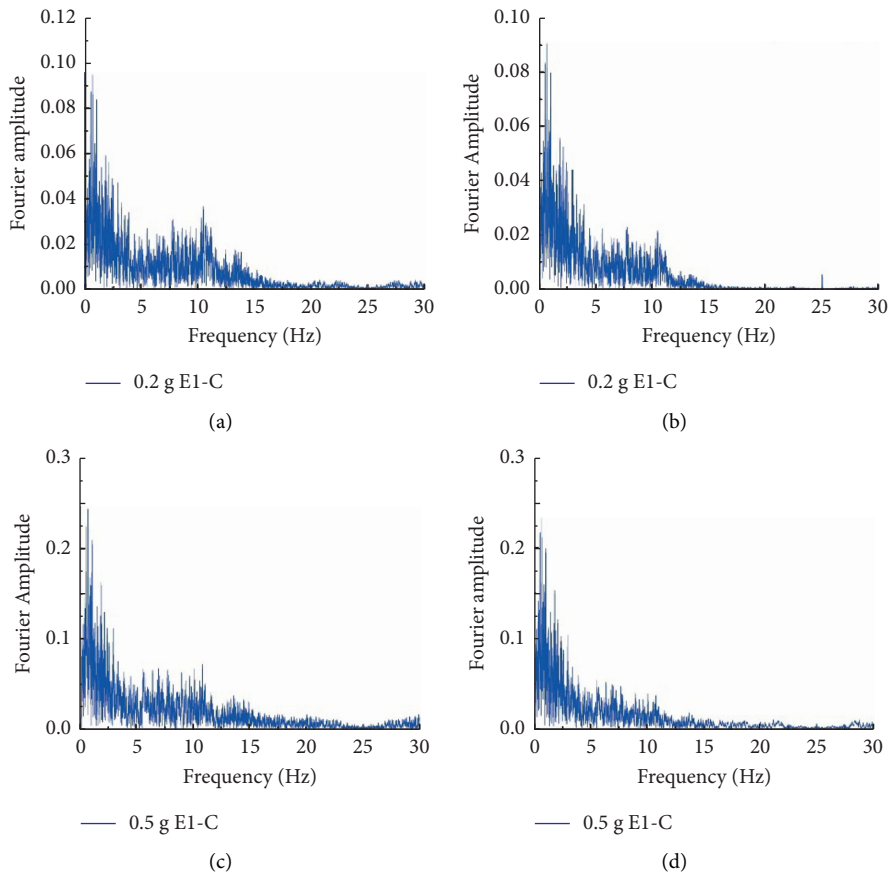Figure 10: Acceleration time history of the monitoring point.

Figure 11: Fourier spectrum of the monitoring point.

TABLE 4: Acceleration amplification factor of pipe sidewall.

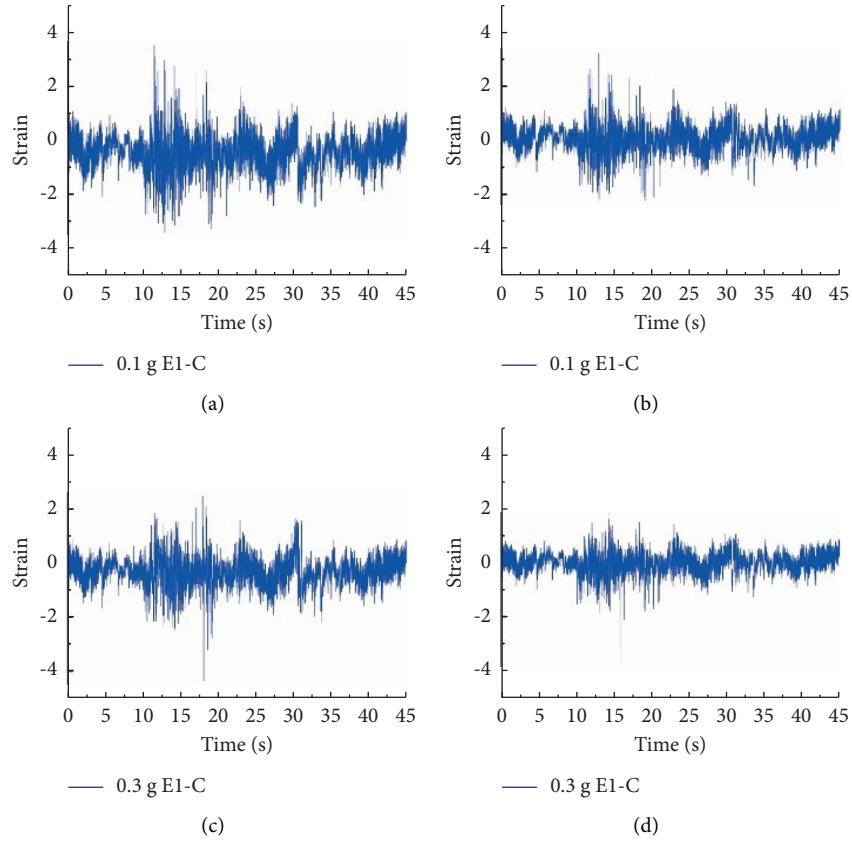| Peak acceleration value (g)	Measuring point	Acceleration amplification factor (considering the effect of contact surface)	Acceleration amplification factor (without considering the effect of contact surface)
0.5	A5	1.88	1.67
	A4	1.52	1.32
	A3	1.21	1.09

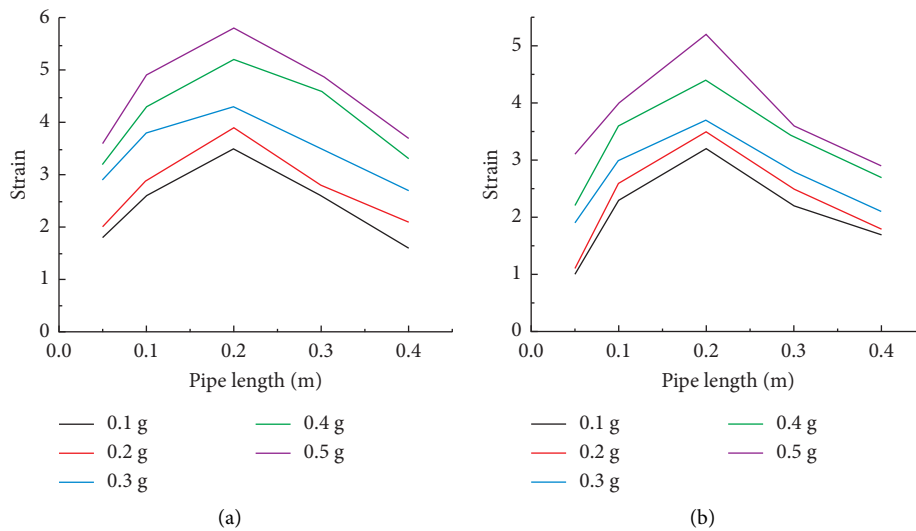FIGURE 12: Structure strain time-history curve at 0.5 g acceleration.

FIGURE 13: Variation curve of the maximum principal stress value of the bottom plate with the length of the structure.

the corresponding maximum principal stress values of the bottom plate are 389.1 kPa, 762.8 kPa, 1088.7 kPa, 1209.5 kPa, and 1401.1 kPa. The former values are 1.18–1.39 times or 21.6%–30.5% greater than the latter (Figure 13).

4. Conclusions

In this paper, a shaking table test is performed for the uniform longitudinal excitation of underground structures in a uniform field (sand). The emphasis is on the impact of the structure-soil contact on the seismic dynamic response characteristics of underground structures.

(1) Plexiglass is used as the model material, and a certain proportion of cement mortar is smeared on its surface as the structure-soil contact surface; direct shear tests are performed on the treated plexiglass tube. The research found that under different normal stress conditions, the plexiglass-sand stress-displacement curve has similar mechanical properties to those of commonly used concrete pipes. Therefore, the test can be performed with plexiglass model material.

(2) Under uniform longitudinal excitation, the underground structure in the uniform field experiences obvious axial strain. Compared with the fully bonded state of the structure-soil interface, when structure-soil contact is considered, the axial strain peak value of the structure is larger; the corresponding stress value of the structure demonstrates an increase of 21.6%–30.5%; and the acceleration response of the structure is more obvious. This is because the existence of the structure-soil contact surface makes the relative displacement between the structures and the soil more obvious, and the structures are more prone to deformation.

If the structure-soil interface is regarded as a complete bond, the structure-soil contact effect is not considered, the seismic design value will be too small, and the project will be in an unsafe state. Therefore, in actual engineering, the existence of the structure-soil interface should be considered to improve the seismic safety of the structure.

(3) This test only involves underground structures in a uniform site, and the seismic wave input is a uniform excitation. The structure-soil contact of underground structures in a nonuniform site under nonuniform excitation should be studied to obtain the seismic dynamic response characteristics of underground structure lines.

Data Availability

The data generated and analysed during the current study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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