Study on Shaking Table Test of Underground Substation Considering Soil-Structure-Equipment Interaction

Zheng Hongyu*, Wen Bo*
*School of Civil Engineering, Xi'an University of Architecture and Technology, Xi'an, Shaanxi.
E-mail: zheng@xauat.edu.cn

Abstract: The electrical equipment has a large quality proportion, and the interaction between equipment and structure cannot be ignored, especially under seismic loads. A 1/25 scale model was designed and made for shaking table test to study its seismic performance, and the acceleration and displacement responses of soil, structure and equipment under unidirectional and bidirectional ground motions were analyzed respectively. The test results show that the acceleration response of the structure and soil increases gradually from bottom to top under the soil-structure-equipment interaction. The acceleration response of equipment is greater than that of the floor where it is located, and it is greater at the position of the side column than that at the position of the central column. The acceleration amplification factor of the soil adjacent to the structure is much larger than that of the soil far away from the structure relative to that at the bottom of the layered shear box.

1. Introduction
With the acceleration of urban construction, underground structure has been widely used in electric power, transportation and national defense engineering. In 1995, six subway stations were seriously damaged in the Hanshin earthquake, and the seismic performance of underground structures began to attract the attention of scholars[1-3]. The underground substation, an important lifeline project, was first built and applied in the United States, Japan and other developed countries in the 1970s. However, at that time, the underground substations were small in scale and basically single buildings, which were less affected by natural disasters such as earthquakes. Therefore, disaster prevention and mitigation were not prominent problems[4]. In 21st century, with the development of large-scale urban construction, the number of underground substations is increasing day by day, and the structure type is more complex. In recent years, the underground structure has been greatly affected by the earthquake, and earthquake and secondary disasters resulting in a large number of personnel and property losses[5]. Therefore, the problem of disaster prevention and mitigation of underground structures, including underground substations, has attracted more and more scholars' attention. Scholars at home and abroad have carried out more in-depth research on the seismic performance of underground engineering structures[6]. According to the static-dynamic coupling between underground structure and surrounding rock system, Du[7] proposed the stress-type viscoelastic artificial boundary condition to establish the soil-structure calculation model of underground structure. Chen[8] studied the elastic seismic response of the underground arch tunnel structure considering the soil-structure interaction, and found that the fixed boundary would cause energy accumulation and increase the structural response. Chen[9] established a simplified seismic calculation model considering soil-structure interaction. In order to verify the theoretical calculation model, shaking table test is often used in seismic performance
analysis of underground structures together with numerical analysis\cite{10,11}. Wen\cite{12} established a three-dimensional finite element model of an underground substation considering the interaction of soil-structure-equipment, and conducted time-history response analysis of seismic performance.

It can be seen from the above research that the types of underground structures are becoming more and more complex, and there are fewer studies on the seismic performance of underground substations involving soil-structure-equipment interaction. In previous studies, this interaction of underground substations was usually ignored, and the seismic response caused by electrical equipment and soil characteristics was ignored. Shaking table test of underground substation was conducted, to study the influence law of soil-structure-equipment interaction on seismic performance of underground substation, and the acceleration and displacement responses of soil, structure and equipment are also studied.

2. Test overview

2.1. Model similarity

The dimensional analysis method is used to calculate the similarity constants of the parameters, to make the model structure reflect the characteristics of the prototype structure as real as possible, the specific similar relationship is shown in Table 1.

| Physical quantity         | Relational expression | Soil    | Similarity ratio | Structure | Equipment |
|---------------------------|-----------------------|---------|------------------|-----------|-----------|
| Length                    | \( S_l \)             | 1/25    | 1/25             | 1/15      |           |
| Linear displacement       | \( S_s \)             | 1/25    | 1/25             | 1/15      |           |
| Area                      | \( S_s = S_l^2 \)     | 1/625   | 1/625            | 1/225     |           |
| Elastic modulus           | \( S_E \)             | 0.075   | 0.075            | 0.045     |           |
| Equivalent density        | \( S_{e,1} = (m_e + m_d)/(S^l m_p) \) | 1.5     | 1.5              | 0.324     |           |
| Strain                    | \( S_s = 1.0 \)       | 1       | 1                |           |           |
| Stress                    | \( S_s = S_s \)       | 0.075   | 0.075            | 0.045     |           |
| Soil shear modulus        | \( G_E = S_E \)       |         |                  |           |           |
| Mass                      | \( S_m = S_m S_l^3 \) | 9.5e-5  | 9.5e-5           | 9.5e-5    |           |
| Time                      | \( S_t = (S_m S_l^2 S_E)^{1/2} \) | 1.79e-1 | 1.79e-1          | 1.79e-1   |           |
| Frequency                 | \( S_f = 1/S_t \)     | 5.59    | 5.59             | 5.59      |           |
| Equivalent acceleration   | \( S_{a,1} = S_E S_m S_t \) | 1.25    | 1.25             | 2.08      |           |

2.2. Model overview

According to the similarity relationship between the prototype and the model, the structure model of shaking table test is simulated by using fine concrete and galvanized iron wire. The main structure that is a two-story frame shear structure of the model is 1/25 of the original structure. The top layer is 155mm high, the bottom layer is 215mm high, the bottom plate is 40mm thick, and the total height of the structure is 410mm. The structural model is shown in Figure 1. The device model is simulated by plexiglass and copper wire, as shown in Figure 2. The undisturbed loess and sawdust loess were selected as the test soil in a ratio of 1:20, as shown in Figure 3. The soil box for the test model is a layered shear box, as shown in Figure 4.
2.3. Measuring point layout

Through the data acquisition of the acceleration, displacement and strain of the soil, structure and equipment during the test, the seismic performance of the underground substation under the soil-structure-equipment interaction is analyzed. The specific arrangement of the sensor is shown in Figure 5.

Three observation surfaces are arranged in the soil: observation surface 1 is far away from the structure and close to the shear box; observation surface 2 and 3 are adjacent to the two sides of the structure respectively. In the figure, $AY$ represents the arrangement of the acceleration sensor along the $Y$ direction, which is used to collect the acceleration response along the long direction of the model system. $AX$ represents the acceleration sensor arranged along the $X$ direction, which is used to collect the acceleration response along the short direction of the model system. $D$ represents the displacement response of the acquisition system along the long direction when the displacement sensor is arranged along the $Y$ direction. $S$ stands for strain gauge, which is used to collect local strain response.

![Figure 5. The specific arrangement of the sensor](image)

2.4. Test conditions

2.4.1. Selection of seismic waves. Two actual strong earthquake records, El Centro wave and Taft wave, were selected according to target response spectrum in the PEER ground motion database. The required artificial wave is generated by software SIMQKE_GR according to the target reaction spectrum. Then the software Shake91 is used to invert the bedrock surface, and the actual ground motion input is obtained. The selected seismic wave is shown in the figure6.
2.4.2. Earthquake input. The loading conditions are divided into seven stages according to the sequence of 7 degree frequent, 8 degree frequent, 9 degree frequent, 8 degree basic, 7 degree rare, 8 degree rare and 9 degree rare earthquake. In each stage, El Centro, Taft and artificial wave are input in turn, and they are input in one direction (Y direction) and two directions (Y Z direction) respectively. Before and after each stage of loading, white noise frequency sweeping was carried out to obtain the dynamic characteristics of the model system. The test loading conditions are shown in table 3.

### Table 2. Test loading conditions

| Working condition | Vibration direction | X | Y | Z | Dimension |
|-------------------|---------------------|---|---|---|-----------|
| White Noise       |                     |   |   |   | Three     |
| Seismic wave      | Y                   | 0 | 1 | 0 | One       |
| White Noise       | Y/Z                 | 0 | 1 | 0.65 | Two |

3. Test results and analysis

3.1. Experimental phenomenon

The post earthquake test phenomena of the model are shown in the figure 7. There are different degrees of cracks in the top soil along the excitation direction and vertical excitation direction. After the test, the whole model did not appear large damage, and the concrete spalling occurred at the intersection of the top beam and the central column. This is consistent with the simulated failure phenomenon in the early stage of the test, and meets the specification requirements of strong column and weak beam, which proves that the test results have achieved good results.

3.2. Acceleration response

3.2.1. Soil acceleration response. Under the action of one-way earthquake, the acceleration amplification factor of soil varies with the depth of soil layer at the observation surface 2, as shown in Figure 8.

Under the action of El Centro wave, the acceleration amplification factor of Y8 gradually decreases from 3.26 to 1.257, with a reduction of 61.4%. Under the action of artificial wave, the amplification...
factor of Y8 acceleration gradually decreases from 2.709 to 1.203, with a reduction of 55.6%. Under the action of Taft wave, the acceleration amplification factor of Y8 gradually decreases from 1.759 to 1.048, with a decrease of 40.4%. The variation of soil acceleration amplification factor with soil depth in observation plane 1 which is adjacent to structure and plane 2 which is far away from the structure are shown in Figure 8.

The acceleration of soil is related to the spectrum characteristics of wave. Under the action of small earthquake, the amplification factor of soil acceleration on observation plane 1 and 2 is larger, and with the increase of input peak acceleration, the amplification factor of soil acceleration decreases gradually. Under the same conditions, when El Centro wave, Taft wave and artificial wave are input, the soil acceleration amplification factor on observation plane 2 is larger than that on plane 1.

Therefore, due to the interaction of soil-structure-equipment, the acceleration response of soil around the structure is greater than that far away from the structure.

Under the action of two-way earthquake, the acceleration amplification factor of soil varies with the depth of soil layer at the observation surface 2, as shown in Figure 9. Under the action of El Centro wave, the acceleration amplification factor of Y8 at the same plane measuring point on the top of the structure decreases from the maximum value of 2.099 to the minimum value of 1.671, with a decrease of 20.39%; under the action of Taft wave, the acceleration amplification factor of Y8 decreases from the maximum value of 1.826 to 1.417, with a decrease of 22.40%; under the action of artificial wave, the acceleration amplification factor of Y8 gradually decreases with the increase of peak acceleration, from the maximum value to the maximum value 864 to the minimum value of 1.444, with a decrease of 49.58%. Under the action of El Centro wave, Taft wave and artificial wave, the change rule of Y14 is consistent with that of Y8, but the acceleration amplification factor of Y14 is less than that of Y8 under the same condition. It can be seen that the soil acceleration amplification factors in the same plane with the top and bottom of the structure decrease with the increase of the peak acceleration.

3.2.2. Structural acceleration response. Accelerometer Y38, Y36 and Y34 are selected on the top, middle and bottom plates of the structure to study the acceleration response of different depth of the
structure under the soil structure equipment interaction. The acceleration amplification factors of the top and middle plates are obtained by comparing Y38 and Y36 with Y34 respectively.

Under the action of one-way earthquake, the variation of structural acceleration amplification factor with depth of the structure is shown in Figure 10. Under the action of El Centro wave, the acceleration magnification factor of the structural roof is reduced from the maximum value of 1.3 to 1.229, which is a decrease of 5.46%. Under the action of Taft wave, the acceleration magnification factor of the structural roof is reduced from the maximum value of 1.239 to 1.089, which is a decrease of 12.06%. Under the action of artificial waves, the acceleration magnification factor of the structural roof showed a decreasing trend as a whole, from the maximum value of 1.178 to 1.035, a decrease of 12.14%. The results show that the acceleration amplification factor of the middle plate is consistent with that of the top plate, and it is smaller than that of the top plate. In conclusion, under the interaction of soil-structure-equipment, the acceleration response of the roof is the largest, the middle plate is the second, and the bottom plate is the smallest.

![Figure 10 Structural acceleration amplification factor (one-way earthquake)](image)

Under the action of two-way earthquake, the variation of structural acceleration amplification factor with depth of the structure is shown in Figure 11. Under the action of El Centro wave, the acceleration amplification factor of the structure decreases continuously. The amplification factor of roof acceleration decreases from 1.303 to 1.221, which decreases by 6.29%; under the action of Taft wave, with the increase of peak acceleration, the amplification factor of structural acceleration decreases as a whole. The amplification factor of roof acceleration decreases from 1.273 to 1.181, decreasing by 7.23%; under the action of artificial wave, with the increase of peak acceleration, the amplification factor of structural acceleration decreases as a whole. Considering the interaction of soil-structure-equipment, the acceleration response of the top plate is the largest, followed by the middle plate and the bottom plate. Therefore, in the case of soil structure equipment interaction, the seismic acceleration response of the structure increases with the increase of the height of the structure.

![Figure 11 Structural acceleration amplification factor (two-way earthquake)](image)

3.2.3. Equipment acceleration response. Y34 is the acceleration reference point of the bottom layer of the structure, Y28 and Y29 are the acceleration reference points of the equipment. The accelerometer Y28 is located on the device 2 which is next to the center column of the structure, and the accelerometer Y29 is located on the device 1 which is next to the side of the structure.
Figure 12 Equipment acceleration response (one-way earthquake)

Figure 12 shows the acceleration amplification factor of the equipment relative to the structural base floor in case of one-way ground motion. It can be seen that the acceleration amplification factors of devices 1 and 2 increase first and then decrease, and all are greater than 1 under the El Centro wave. In case E5, the equipment acceleration amplification factor at the middle and edge of the structure is peak which are 1.197 and 1.163 respectively. Under the Taft wave, the acceleration amplification factors of equipment 1 and 2 decrease gradually. In case T1, the acceleration amplification factor reaches the peak value of 1.146 and 1.145 respectively. When the artificial wave is applied, the acceleration amplification factors of equipment 1 and 2 first increase and then decrease. Under R4 condition, the acceleration amplification factor reaches the peak value of 1.204 and 1.113 respectively. Under any working condition, the acceleration amplification factor of equipment 1 is greater than 1, but equipment 2 is not. The main reason is that the equipment in the middle of the structure has a small response under earthquake action and the acceleration amplification factor is less than 1. In conclusion, with the soil-structure-equipment interaction, the acceleration response of the equipment is greater than that of the structural base floor, and the acceleration response of equipment 1 is greater than that of equipment 2.

Figure 13 Equipment acceleration response (two-way earthquake)

Figure 13 shows the acceleration amplification factor of the equipment relative to the structural base floor in case of two-way ground motion. The acceleration amplification factors of equipment 1 and 2 are greater than 1, and the maximum values are 1.24 and 1.142 respectively in case of El Centro wave. The acceleration amplification factors of equipment 1 and 2 gradually decrease, and the maximum values are 1.146 and 1.079 respectively in case of Taft wave. The acceleration amplification factors of equipment 1 and 2 decrease in turn, and the maximum values are 1.123 and 1.058 respectively in case of Artificial wave. Under the action of El Centro wave, the acceleration response of equipment 1 and 2 relative to the structural base floor is larger than that of Taft wave and artificial wave. Comparing the acceleration amplification factors of equipment 1 and 2, it can be seen that the acceleration response of the equipment in the middle of the structure is less than that in the edge of the structure.
3.3. Displacement response

3.3.1. Structural layer displacement. The displacement of the top floor of the structure is obtained by subtracting the displacement of the top plate and the displacement of the middle plate, and the displacement of the bottom floor is obtained by subtracting the displacement of the middle plate and the bottom plate. Table 3 shows the displacement values of the top and bottom floors under different peak accelerations under the one-way seismic wave. It can be seen that the displacement between the top and bottom layers of the structure increases with the increase of input peak acceleration, and the inter layer displacement of the top layer of the structure is greater than that of the bottom layer. The maximum displacement between the top and bottom layers of the structure is 0.610mm and 0.731mm respectively under the El centro wave; The maximum displacement between the top and bottom layers of the structure is 0.630mm and 0.770mm respectively under the Taft wave; The maximum displacement between the top and bottom layers of the structure is 0.576mm and 0.7mm respectively, under artificial wave.

Table 3  Displacement between structural layers/mm (one-way earthquake)

| Seismic wave | Working condition | 7 degree frequent earthquake | 8 degree frequent earthquake | 9 degree frequent earthquake | 8 degree basic earthquake | 7 degree rare earthquake | 8 degree rare earthquake | 9 degree rare earthquake |
|--------------|-------------------|-----------------------------|-----------------------------|-----------------------------|--------------------------|--------------------------|--------------------------|--------------------------|
| El centro    | First floor        | 0.107                       | 0.133                       | 0.162                       | 0.240                    | 0.280                    | 0.485                    | 0.610                    |
|              | second floor       | 0.148                       | 0.156                       | 0.220                       | 0.350                    | 0.422                    | 0.570                    | 0.73                     |
| Taft         | First floor        | 0.123                       | 0.160                       | 0.200                       | 0.250                    | 0.251                    | 0.440                    | 0.630                    |
|              | second floor       | 0.159                       | 0.233                       | 0.280                       | 0.325                    | 0.340                    | 0.621                    | 0.770                    |
| Artificial wave | First floor        | 0.105                       | 0.143                       | 0.152                       | 0.208                    | 0.230                    | 0.450                    | 0.576                    |
|              | second floor       | 0.157                       | 0.201                       | 0.227                       | 0.310                    | 0.350                    | 0.570                    | 0.710                    |

Table 4 shows the displacement values of the top and bottom floors under different peak accelerations under the two-way seismic wave. It can be seen that: the variation law of the interlayer displacement of the top and bottom layers of the structure is consistent with that of the one-way seismic wave. The maximum displacement between the top and bottom layers of the structure is 0.266mm and 0.364mm respectively under the El centro wave; The maximum displacement between the top and bottom layers of the structure is 0.261mm and 0.372mm respectively under the Taft wave; The maximum displacement between the top and bottom layers of the structure is 0.259mm and 0.362mm respectively, under artificial wave. By comparing the displacement of the structure under one-way earthquake and two-way earthquake, it can seen that: the two-way ground motion makes the displacement of the structure larger in the same seismic intensity.

Table 4  Displacement between structural layers/mm (two-way earthquake)

| Seismic wave | Working condition | 7 degree frequent earthquake | 8 degree frequent earthquake | 9 degree frequent earthquake | 8 degree basic earthquake |
|--------------|-------------------|-----------------------------|-----------------------------|-----------------------------|--------------------------|
| El centro    | First floor        | 0.141                       | 0.193                       | 0.266                       | 0.258                    |
|              | second floor       | 0.175                       | 0.271                       | 0.364                       | 0.360                    |
| Taft         | First floor        | 0.151                       | 0.200                       | 0.243                       | 0.261                    |
|              | second floor       | 0.213                       | 0.284                       | 0.307                       | 0.372                    |
| Artificial wave | First floor        | 0.146                       | 0.176                       | 0.251                       | 0.259                    |
|              | second floor       | 0.208                       | 0.253                       | 0.347                       | 0.362                    |
3.3.2. Interlayer displacement angle of structure. Table 5 and 6 show the interlayer displacement angles of the top and bottom layers of the structure under different seismic intensities. It can be seen that the interlayer displacement angle of the structure increases with the increase of the peak acceleration, except that the angle of top layer is slightly greater than 1/250 under the rare earthquake of 9 degrees Taft wave, the others are less than 1/250. Comparing the interlayer displacement angle under one-way and two-way seismic action, it can be seen that the soil-structure-equipment interaction has a greater impact on the interlayer displacement angle of the structure under two-way ground motion.

| Seismic wave | Working condition | 7 degree frequent earthquake | 8 degree frequent earthquake | 9 degree frequent earthquake | 7 degree basic earthquake | 8 degree rare earthquake | 9 degree rare earthquake |
|--------------|-------------------|-----------------------------|-----------------------------|-----------------------------|--------------------------|-------------------------|-------------------------|
| El centro    | Top floor         | 1/1448                      | 1/1165                      | 1/956                       | 1/646                    | 1/553                   | 1/323                   | 1/254                   |
|              | Bottom floor      | 1/1723                      | 1/1634                      | 1/1159                      | 1/728                    | 1/607                   | 1/447                   | 1/349                   |
| Taft         | Top floor         | 1/1260                      | 1/968                       | 1/775                       | 1/620                    | 1/620                   | 1/352                   | 1/246                   |
|              | Bottom floor      | 1/1603                      | 1/1108                      | 1/910                       | 1/796                    | 1/750                   | 1/411                   | 1/331                   |
| Artificial wave | Top floor     | 1/1476                      | 1/1083                      | 1/1019                      | 1/745                    | 1/674                   | 1/344                   | 1/269                   |
|              | Bottom floor      | 1/1624                      | 1/1268                      | 1/1123                      | 1/822                    | 1/728                   | 1/447                   | 1/438                   |

| Seismic wave | Working condition | 7 degree frequent earthquake | 8 degree frequent earthquake | 9 degree frequent earthquake | 8 degree basic earthquake | 9 degree rare earthquake |
|--------------|-------------------|-----------------------------|-----------------------------|-----------------------------|--------------------------|-------------------------|
| El centro    | Top floor         | 1/1099                      | 1/803                       | 1/583                       | 1/601                    |                         |                         |
|              | Bottom floor      | 1/1457                      | 1/941                       | 1/700                       | 1/708                    |                         |                         |
| Taft         | Top floor         | 1/1026                      | 1/775                       | 1/638                       | 1/594                    |                         |                         |
|              | Bottom floor      | 1/1197                      | 1/899                       | 1/830                       | 1/685                    |                         |                         |
| Artificial wave | Top floor     | 1/1061                      | 1/880                       | 1/617                       | 1/598                    |                         |                         |
|              | Bottom floor      | 1/1226                      | 1/1008                      | 1/735                       | 1/704                    |                         |                         |

4. Conclusion

(1) Under the interaction of soil structure equipment, the soil acceleration amplification factor increases gradually from bottom to top. With the increase of peak acceleration, the amplification factor of soil acceleration decreases gradually.

(2) Under the interaction of soil, structure and equipment, the acceleration response at different heights of the structure changes as follows: under the same working condition, the acceleration response of the top plate is the largest, followed by the middle plate, and the bottom plate is the smallest.

(3) Under the same working condition, the acceleration response of the equipment is greater than that of the structural floor, and the acceleration response of the edge equipment is greater than that of the intermediate equipment.

(4) In the case of two-way ground motion, the interlayer displacement of structure is larger under the interaction of soil-structure-equipment.

Acknowledgments

The authors wish to express their gratitude towards the Major Program of the National Natural Science Foundation (No. 51590914) (in China), the National Natural Science Foundation Project (No. 51578450, No. 51378225) (in China).
References

[1] Chang S E, Rose A Z, Shinozuka M, et al. Modeling earthquake impact on urban lifeline systems: advances and integration in loss estimation[J]. Earthquake engineering frontiers in the new millennium, 2001, 195.

[2] Uenishi K, Sakurai S. Characteristic of the vertical seismic waves associated with the 1995 Hyogo-ken Nanbu (Kobe), Japan earthquake estimated from the failure of the Daikai Underground Station[J]. Earthquake Engineering & Structural Dynamics, 2000, 29(6): 813-821.

[3] Hashash Y M A, Hook J J, Schmidt B, et al. Seismic design and analysis of underground structures[J]. Tunnelling and underground space technology, 2001, 16(4): 247-293.

[4] St John C M, Zahrah T F. Aseismic design of underground structures[J]. Tunnelling and underground space technology, 1987, 2(2): 165-197.

[5] Goel R K, Singh B, Zhao J. Underground infrastructures: planning, design, and construction[M]. Butterworth-Heinemann, 2012.

[6] Chian S C, Tokimatsu K. Floatation of underground structures during the M w 9.0 Tōhoku Earthquake of 11th March 2011[C]. Proceedings of the 15th World Conference on Earthquake Engineering, 2012.

[7] Zhao Mi, Wang Litao, Du Xiuli, et al. Comparison of Earthquake Input Methods in Soil-structure Interaction Analysis[J]. Technology for Earthquake Disaster Prevention, 2017, 12(03): 589-598. (in Chinese)

[8] Chen H L, Jin F N, Fan H L. Elastic responses of underground circular arches considering dynamic soil-structure interaction: A theoretical analysis[J]. Acta Mechanica Sinica, 2013, 29(1): 110-122.

[9] CHEN G X, Zuo X, WANG Z H, et al. Shaking table model test of subway station structure under far field and near field ground motion[J]. Journal of Zhejiang University (Engineering Science), 2010, 44(10): 1955-1961.

[10] Guoxing C, Su C, Xi Z, et al. Shaking-table tests and numerical simulations on a subway structure in soft soil[J]. Soil Dynamics and Earthquake Engineering, 2015, 76: 13-28.

[11] Chen S, Zhuang H, Quan D, et al. Shaking table test on the seismic response of large-scale subway station in a loess site: A case study[J]. Soil Dynamics and Earthquake Engineering, 2019, 123: 173-184.

[12] Wen B, Zhang L, Niu D, et al. Soil–structure–equipment interaction and influence factors in an underground electrical substation under seismic loads[J]. Applied Sciences, 2017, 7(10): 1044.