Shaking table test on multi-dimensional seismic response of structure and nuclear power equipment coupled system

Binbin Li, Weifeng Xu, Sheliang Wang, Bo Liu, Yang Liu and Qingyun Zhao, Lu He

1School of Civil Engineering, Xi’an University of Architecture and Technology, Xi’an, Shaanxi, 710055, China
2School of Urban Planning and Municipal Engineering, Xi’an Polytechnic University, Xi’an, Shaanxi, 710048, China
3Shaanxi Metallurgical Design & Research Institute Co., Ltd., Xi’an, Shaanxi, 710032, China
4Key Laboratory of Structural Engineering and Earthquake Resistance, Ministry of Education (XAUAT), Xi’an, Shaanxi, 710055, China
5e-mail: libinbin@xauat.edu.cn, 6e-mail: weifengxu@xauat.edu.cn,
7e-mail: sheliangw@163.com, 8e-mail: 1131757110@qq.com,
9e-mail: yangliu@xpu.edu.cn, 10e-mail: 3294066230@qq.com,
11e-mail: 625668019@qq.com
*Corresponding author’s e-mail: weifengxu@xauat.edu.cn

Abstract: Structure and nuclear power equipment coupled system in nuclear power plant has complex dynamic interaction under seismic action. In order to study the seismic response of coupled system and assess seismic capacity of nuclear power equipment, shaking table test on coupled system by multi-dimensional seismic action was carried out. The natural frequency and damping ratio of the structure and nuclear power equipment were measured by two dynamic characteristic tests before and after the test. Further more, the test also included five operating basis earthquakes and one safe shutdown earthquake by using the artificial seismic waves as seismic inputs. The test results show that the dynamic amplification effect of the coupled system is obvious, and acceleration amplification factor of the equipment in the coupled system is about two times of the equipment directly connected to the shaking table in the X direction, between one and two times in the Y and Z direction. Compared with the structure, the dynamic response of the equipment in the coupled system also has a certain degree of amplification effect. In addition, the dynamic characteristics of structure and equipment change little. The equipment works well under all the test conditions, meeting the seismic requirements.

1. Introduction
Earthquake is a very destructive and unpredictable natural disaster. If it causes damage to nuclear power plant and lets radioactive materials to be released, the consequences are unimaginable. Therefore, it is of special importance to ensure the safe operation of important structures and...
equipment in nuclear power plant under earthquake action. The design of important structures and equipment in nuclear power plant must meet the requirement of earthquake resistant design code. As a test method widely used in simulating earthquake, shaking table test technology is regarded as a necessary part in the equipment qualification process by the relevant specifications of nuclear power equipment [1-6].

There are many researches about the shaking table test on nuclear power equipment. Hong et al. [7] carried out the dynamic characteristics test and shaking table test of IS single-stage single suction water centrifugal pump. Cho et al. [8] conducted shaking table test on the cabinet of nuclear power plant, and observed that the dynamic stiffness of cabinet decreased with the increase of excitation level, and established a simplified model for nonlinear seismic response analysis of cabinet of nuclear power plant. Shi et al. [9-11] conducted shaking table tests on the circulating fan, hydrogen elimination fan, 1E emergency diesel generator oil pump and outlet box of the nuclear power plant, including two white noise frequency sweeps at the beginning and ending of test, five operating basis earthquake (OBE) and one safe shutdown earthquake (SSE). The requirements of artificial ground motion input in the test were discussed, and the test equipment had passed the seismic assessment test. Gao et al. [12] conducted five OBE and one SSE three-dimensional artificial ground motion input shaking table tests on a nuclear grade primary water accident pump. Before and after the test, the integrity and function of the equipment were normal, and the seismic performance was good. Zhou et al. [13] carried out shaking table test research on a 1E cooling water pump motor, and used high confidence and low probability failure to quantify the seismic margin of the equipment. The main parameters such as response spectrum clipping factor and suppression factor were reasonably selected to calculate the seismic margin of the test motor. However, at present, the research of shaking table test on nuclear power equipment mostly rigidly connects nuclear power equipment with shaking table surface, while the research of shaking table test on structure and nuclear power equipment coupled system is less. Under the action of multi-dimensional earthquake, structure and nuclear power equipment coupled system connected by expansion bolt in nuclear power plant has complex dynamic interaction, and the seismic response is difficult to predict. Therefore, studying the seismic response of structure and nuclear power equipment coupled system under multi-dimensional seismic action is of great significance to the seismic design of nuclear power equipment and the safe operation of nuclear power plants.

In order to simulate the stress state of the coupled system in the real environment, the shaking table test in this paper uses the expansion bolts specially used in the nuclear power plant to connect the nuclear power equipment with the supporting structure. A total of five OBE and one SSE dynamic time history excitation, and two dynamic characteristic tests at the beginning and end of the shaking table test are carried out to analyze the multi-dimensional seismic response of structure and nuclear power equipment coupled system under all the test cases. The damage of coupled system before and after the test is compared, and the seismic performance of nuclear power equipment is evaluated.

2. Materials and Methods

2.1. Test equipment and object

2.1.1. Test equipment

The MTS three-dimensional six-degree-of-freedom seismic simulation shaking table test system in Key Laboratory of Structural Engineering and Earthquake Resistance (XAUAT) was used in the test. The size of the shaking table is 4.1m × 4.1m, which maximum bearing capacity is 30t, and the test frequency is 0. 1 ~ 100 Hz. The maximum acceleration (no load) is 4.0g in horizontal X direction, 3.8g in horizontal Y direction and 6.0g in vertical Z direction.

LMS test lab intelligent dynamic signal acquisition analyzer is used for data acquisition, and the number of channels is 128. PCB acceleration sensor is used for acceleration sensor, and its frequency response is 0.5 ~ 100 Hz.
2.1.2. Test object and installation
The prototype of nuclear power equipment in the test is the prototype equipment of low voltage AC distribution box, DC distribution box and dual power switching distribution box of a certain type of nuclear power plant. The structure connected with the equipment in the test is a shear wall with concrete grade of C40, main reinforcement of HRB400 and stirrup of HPB235.

In the test, the low voltage AC distribution box and DC distribution box are connected with the shear wall through the special expansion bolts for nuclear power, and the shear wall is connected with the shaking table through the reserved holes. The dual power switching distribution box is rigidly connected with the shaking table through the rigid support with M25 bolts. After the test object is installed and fixed, it is shown in Figure 1.

![Figure 1. Test objects after installation and fixation.](image)

2.1.3. Arrangement of measuring points and regulations of coordinate axis
According to the requirements and test methods of the code and seismic test of nuclear power equipment [1-3], five acceleration measuring points are arranged on the shaking table and test objects. Five acceleration measuring points are recorded as A1, A2, A3, A4, A5. A1 measuring point is arranged on the shaking table to test the seismic input of the table. A2 measuring point is arranged on the dual power switching distribution box to test the seismic response. A3 measuring point is arranged on the DC distribution box. A4 measuring point is arranged on the low-voltage AC distribution box. A5 measuring point is arranged at the top of the shear wall to test the seismic response of the structure. The five measuring points all contain X, Y and Z components, so a total of 15 PCB acceleration sensors are arranged. The specific measuring point position and coordinate axis are shown in Figure 2.

![Figure 2. Layout of acceleration measuring points and schematic diagram of coordinate axis.](image)
2.2. Test contents and methods

2.2.1. Measurement of dynamic characteristics of test object
Firstly, the first dynamic characteristic test is carried out, followed by five OBE and one SSE seismic assessment tests, and finally the second dynamic characteristic test is carried out. The dynamic characteristic test adopts white noise random wave with frequency range of 0.5Hz ~ 100Hz and acceleration amplitude of 0.2g. White noise random waves are excited simultaneously in X, Y and Z directions of the shaking table to measure the dynamic characteristics of the test object.

2.2.2. Seismic qualification test
In the seismic qualification test, the seismic wave input is based on the floor response spectrum provided by the designer. First, the required response spectrum (RRS) is made, and then the artificial seismic wave is generated by transformation calculation. The artificial seismic wave is used as the input signal of the shaking table for seismic test. According to the standards, the test response spectrum (TRS) generated by the test artificial seismic wave shall envelope the whole frequency band of the RRS. To ensure the independence of the input three direction artificial seismic waves, the average value of the coherence function should be less than 0.5, and the absolute value of the correlation function should be less than 0.3 \cite{3}. The damping ratio of artificial seismic wave is 5\% and the spectrum value of OBE condition is 80\% of SSE condition in this test. The time history curves of artificial seismic wave input under OBE and SSE condition are shown in Figure 3 and Figure 4, and from left to right are X, Y and Z directions. (Figure(a) is the X direction, and Figure(b) is the Y direction, and Figure (c) is the Z direction.)

![Figure 3. Time history curve of artificial seismic wave of OBE.](image)

![Figure 4. Time history curve of artificial seismic wave of SSE.](image)

2.2.3. Function monitoring and visual inspection
In the process of seismic qualification test, it is necessary to monitor the working state of low-voltage AC distribution box, DC distribution box and dual power switching distribution box, and to monitor whether the function of the system and components is normal. After the seismic qualification test, it is necessary to visually check the structural integrity of the tested equipment. There should be no cracks in the structure. Bolts and nuts shall not be loose or fall off. There should be no crack or tear in the weld. Electrical components should not be loose and other abnormal phenomena.
3. Results & Discussion

3.1. Dynamic characteristics of structure and equipment

The natural frequency and damping ratio of the structure and equipment are measured by using white noise acoustic wave in the direction of X, Y and Z orthogonal axes. Taking the first white noise condition in X direction of A4 measuring point as an example, the transfer function is calculated by MATLAB to obtain the amplitude frequency curve and phase frequency curve, as shown in Figure 5, and then the damping ratio is calculated by half power method [14-16]. The natural frequency and damping ratio of the test structure and equipment are shown in Table 1.

![Figure 5. Amplitude frequency and phase frequency curves of A1 measuring point in the X direction.](image)

Table 1. Natural frequencies and damping ratios of structure and equipment along three directions.

| Measuring point | Name                               | Direction | Frequency (Hz) | Damping ratio (%) |
|-----------------|------------------------------------|-----------|----------------|------------------|
| A2              | Dual power switching distribution box | X         | 24.71          | 6.3              |
|                 |                                    | Y         | 28.80          | 6.1              |
|                 |                                    | Z         | 27.85          | 4.4              |
| A3              | DC distribution box                | X         | 20.34          | 4.0              |
|                 |                                    | Y         | 29.71          | 3.5              |
|                 |                                    | Z         | 20.34          | 1.9              |
| A4              | Low voltage AC distribution box    | X         | 20.38          | 5.8              |
|                 |                                    | Y         | 24.55          | 4.8              |
|                 |                                    | Z         | 20.38          | 3.3              |
| A5              | Shear wall                         | Y         | 29.54          | 3.5              |
|                 |                                    | Z         | 29.69          | 1.7              |

After the seismic test, the second white noise acoustic excitation was carried out. According to the data calculation results, it is found that the values are basically consistent with those in Table 1, which indicates that there is no damage to the structure and equipment before and after the test.

3.2. Dynamic response

According to the test results, TRS can completely envelop RRS under all the test conditions, and the absolute value of correlation function is less than 0.2, which meets the requirements of the specification. Due to space limitation, only three direction acceleration spectrum and correlation function under SSE condition are given, as shown in Figure 6 and Figure 7. In Figure 6, Figure (a) is the X direction, and Figure (b) is the Y direction, and Figure (c) is the Z direction. The acceleration peak values of each measuring point under five OBE and one SSE conditions are shown in Table 2.
Figure 6. Response spectrum of artificial seismic wave of SSE.

Figure 7. Correlation function diagram of artificial seismic wave of SSE.

Table 2. Maximum accelerations of measuring points

| Measuring point | Direction | OBE1 | OBE2 | OBE3 | OBE4 | OBE5 | SSE   |
|-----------------|-----------|------|------|------|------|------|-------|
| A1              | X         | 0.96 | 0.98 | 0.98 | 0.98 | 0.99 | 1.32  |
|                 | Y         | 1.15 | 1.15 | 1.16 | 1.16 | 1.16 | 1.56  |
|                 | Z         | 0.92 | 0.94 | 0.90 | 0.92 | 0.94 | 1.23  |
| A2              | X         | 0.96 | 0.98 | 0.98 | 0.98 | 0.99 | 1.33  |
|                 | Y         | 1.18 | 1.18 | 1.16 | 1.17 | 1.17 | 1.57  |
|                 | Z         | 0.93 | 0.92 | 0.90 | 0.92 | 0.92 | 1.21  |
| A3              | X         | 2.01 | 1.98 | 2.11 | 2.10 | 2.08 | 2.97  |
|                 | Y         | 1.47 | 1.43 | 1.45 | 1.46 | 1.47 | 1.86  |
|                 | Z         | 0.98 | 0.94 | 0.96 | 0.97 | 0.94 | 1.26  |
| A4              | X         | 1.86 | 1.84 | 1.95 | 1.99 | 2.03 | 2.64  |
|                 | Y         | 2.18 | 2.17 | 2.12 | 2.28 | 2.20 | 3.10  |
|                 | Z         | 1.28 | 1.29 | 1.25 | 1.30 | 1.26 | 1.73  |
| A5              | X         | 1.64 | 1.65 | 1.68 | 1.74 | 1.81 | 2.49  |
|                 | Y         | 1.43 | 1.44 | 1.49 | 1.50 | 1.51 | 1.93  |
|                 | Z         | 0.97 | 1.01 | 0.99 | 1.00 | 1.01 | 1.31  |

3.3. Acceleration amplification factor

The acceleration amplification factors of structure and equipment under OBE and SSE conditions are compared, as shown in Figure 8. In Figure 8, Figure (a) shows the point of A2, and Figure (b) shows the point of A3, and Figure (c) shows the point of A4, and Figure (d) shows the point of A5. It can be seen from the figure that under all test conditions the value of acceleration amplification factor in X and Y directions of A4 measuring point fluctuates around 2, which has significant dynamic amplification effect, which is more prominent than that in Z direction. The X direction amplification coefficient of A3 is larger than 2, Y and Z directions are between 1 and 1.5, and the X direction amplification effect is the strongest. The acceleration amplification factor of A2 measuring point in three directions is about 1, which almost makes rigid body translation with the shaking table table, and indicates no amplification effect. The acceleration amplification factor in three directions of A5 is bigger than 1, and the amplification effect in X direction is more significant than that in Y and Z.
Figure 8. Acceleration amplification factors of measuring point under OBE and SSE conditions.

Comparing A2, A3 and A4, it is found that the acceleration amplification factor of the equipment in the coupled system is about two times of the equipment directly connected to the shaking table in the X direction, and 1 ~ 2 times in the Y and Z directions. The dynamic amplification effect is significant, which indicates that the equipment in the coupled system will bear greater seismic action under multi-dimensional seismic action. Comparing A3, A4 and A5, the average value of acceleration amplification factor of A3 and A4 is larger than that of A5, which indicates that the equipment in the coupled system has a certain degree of dynamic amplification effect compared with the structure itself.

3.4. Other index
Through the function monitoring, it is found that the equipment works normally, and there is no change in various functional indexes. Through the inspection, it is found that the bolts and nuts are not loose or fall off, and the expansion bolts at the coupled system connection are not loose. The equipment and structure have no crack, no damage and deformation, and the structural integrity is good, which also confirms that the dynamic characteristics of the structure and equipment have little change and no damage.

4. Conclusions
In this paper, shaking table test on multi-dimensional seismic response of structure and nuclear power equipment coupled system includes two dynamic characteristics tests, five OBE and one SSE seismic qualification tests. The following conclusions are obtained:

- Through two dynamic characteristic tests, it is found that the natural frequency and damping ratio of structure and nuclear power equipment coupled system before and after the test almost have no change, so the coupled system basically has no damage.

- Under the multi-dimensional seismic action, the acceleration amplification factor of the equipment in the coupled system is about two times of the equipment directly connected to the shaking table in the X direction, and 1 ~ 2 times in the Y and Z directions. The dynamic amplification effect is obvious, which indicates that the equipment in the coupled system will
bear greater seismic action.

- Compared with the structure, the equipment in the coupled system also has a certain degree of dynamic amplification effect under multi-dimensional seismic action.
- Before and after the shaking table test, the structure and nuclear power equipment coupled system have no damage, and the structural integrity is good. The equipment works normally, and there is no change in various functional indexes. The equipment meets the seismic requirements.

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