SHAKING TABLE TEST OF HIGH-TEMPERATURE GAS-COOLED REACTOR PLANT

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Abstract

The reactor plant of High temperature gas cooled reactor building is the last barrier to prevent the leakage of radioactive materials, so the seismic performance is of high important. In order to investigate the seismic performance of the reactor plant, spent fuel plant, auxiliary plant, a 1/20 scale particle concrete model was designed and constructed. Horizontal bidirectional seismic wave, which included two natural waves and three artificial waves, were selected as the input waves in the shaking table model test. The dynamic responses of the model were obtained from the acceleration sensors and displacement sensors. The result showed that the maximum acceleration magnification factor of the model was 2.4 under the design of ground motion. The displacement at the top of the reactor plant was small. The model was within the elastic range as a whole and had a good seismic performance.

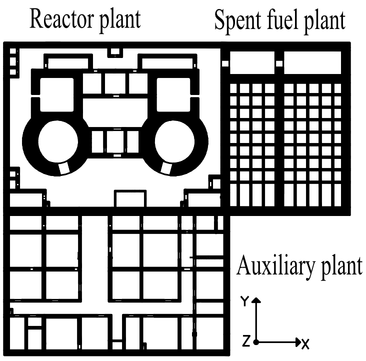
Keywords: High-temperature Gas-cooled Reactor Plant, Seismic performance, Shaking table test.

1. Introduction

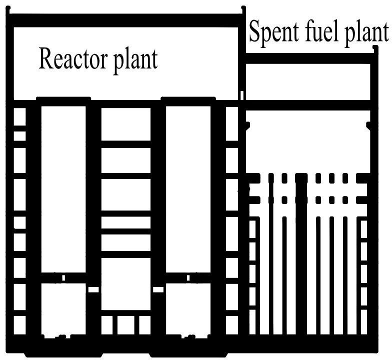
The reactor plant is the last barrier to prevent the leakage of radioactive[1]. In 2011, Japan's Fukushima nuclear accident occurred because the reactor broke in an earthquake and a mass of radioactive materials leaked out, which seriously threatened life and property. Earthquakes are one of the critical factors leading to the failure of nuclear power plants, so the seismic safety analysis of the reactor is very important.

Model tests and numerical simulation analyses are two main ways to study the seismic performance of Nuclear Power Plant (NPP). Qian et al.[2] verified the seismic safety of the pre-stressed concrete containment vessel (PCCV) for CNP1000 nuclear power plant by conducting a series of single degree of freedom (SDOF) pseudo-dynamic tests of 1/10 scale model. Wang et al. [3] carried out shaking table tests of a 1/15 model reinforced concrete containment vessel (RCCV) with less ballast to verify the seismic performance of a prototype RCCV under its design earthquake level of SL-2. Chen et al. [4] constructed a scaled-down RCCV structure of advanced boiling water reactor (ABWR) for seismic test on the shaking table. Yoshio Kitada[5] conducted shaking table tests on the reactor building, adjacent turbine building and nuclear auxiliary building, and investigated the interaction between three adjacent buildings.

Huaneng Shidaowan High-Temperature Gas-Cooled Reactor Nuclear Power Plant was the first demonstration project in the world to successfully commercialize fourth-generation nuclear power technology. This paper combined the high-temperature gas-cooled reactor nuclear power plant with a scale model to conduct a shaking table test to analyze the seismic performance of the structure. The nuclear island plant of the nuclear power plant includes a reactor plant, a nuclear auxiliary plant, and a spent fuel plant. The structure diagram is shown in Fig. 1.



(a)



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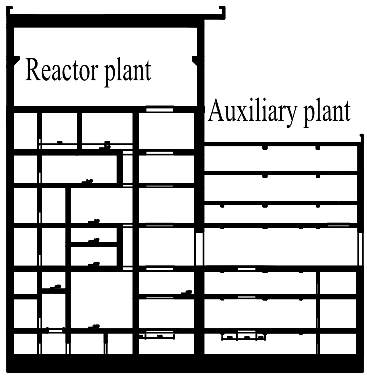


(c)

Fig. 1 NPP layout. (a) Plan graph. (b) Reactor and spent fuel direction profile. (c) Reactor and auxiliary direction profile

2. Model design and experimental set-ups

2.1 Similitude requirements and construction of model

In order to truthfully simulate the dynamic response of prototype NPP under earthquake through shaking table model test, it is necessary to take into account the similitude requirements. Complete similitude can be obtained if there is similarity between the model and prototype with respect to lengths, forces and times. Selecting length, L, Young's modulus, E, and density, ρ, as the fundamental physical quantities, then the other physical quantities can be expressed by these three fundamental quantities according to the Buckingham's p-Theorem. The size of the shaking table used in the experiment was 5 m × 5 m, the maximum load was 30 t, and the maximum acceleration at full load was 2.0 g. In this paper, the length scale

λ_L=1/20 was determined based on the space available and capacity of the shaking table. Particulate concrete was used for model making. Similitude relationships is shown in Table 1

Table 1 Similitude requirements of model

Types	Physical quantity	Dimension	Similitude ratio
Geometry property	Length	$[L]$	S_L = 1/20
Material properties	Young's modulus	$[FL^{-2}]$	S_E = 1/4
	Density	$[FL^{-4}T^2]$	S_ρ = 1
	Equivalent mass density	$[FL^{-4}T^2]$	$S_{\rho e}$ = 1
Dynamic properties	Time	$[T]$	S_T = 0.1
	Acceleration amplitude	$[FL^{-2}]$	S_α = 5
	Frequency	$[T^{-1}]$	S_v = 10

The factory building model is an overall closed structure. After the construction is completed, the internal template cannot be removed. In order to minimize the impact of the template on the structure and not hinder the construction of the model, the internal template was made of foam and the reinforcement was replaced by steel wire mesh. The reactor plant and spent fuel plant were made according to the prototype drawing, and the auxiliary building was simplified for the internal wall equivalent stiffness. The proportion of particulate concrete used in making the model was selected as cement: yellow sand: lime: water = 1: 0.5: 0.6: 1.88. The construction of the model is shown in Fig. 2. After the construction was completed, the total weight of the model reached 30t, which is the maximum bearing capacity of the shaking table.

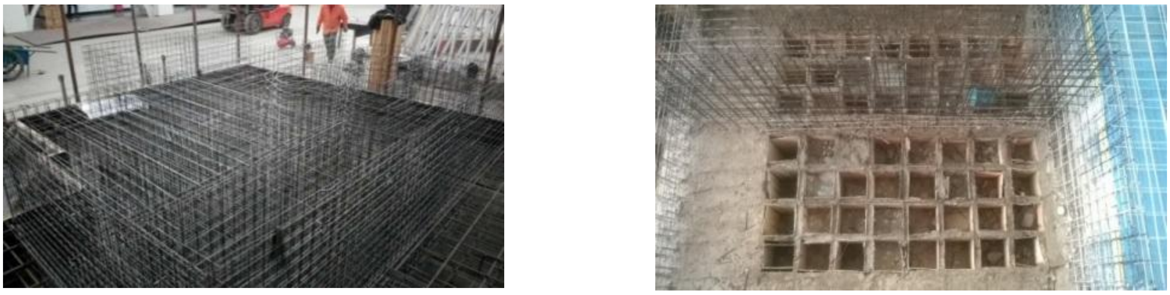


Fig. 2 Model construction

2.2 Measurement arrangement

The test used a three-directional acceleration sensor to measure the acceleration response of the structure. The layout is shown in Fig. 3. A1 was fixed on the base plate. A2 was fixed on the vertical support of the pressure vessel. A3 ~ A5 were fixed on the floor where important equipment were installed. A7 was fixed at the top center of the reactor plant. Cable displacement sensors were used to measure the displacement of floors. Because the structure was closed after the construction was completed, the sensors of A2-A6 were arranged in advance during the construction. 7 sets of strain gauges were evenly arranged from bottom to top along the outer wall of the model.

2.3 The input earthquake waves

Five ground motions were used for comparison, including two natural waves and three artificial waves. The natural waves were selected according to the site spectrum (SL-2) provided by the site safety evaluation report, and finally determined as San Fernando and Parkfield waves. The artificial waves were generated from the SL-2 spectrum, Uniform Hazard Spectrum (UHS)[6] and RG1.60 spectra, respectively. The response spectra of the five seismic waves are shown in Fig. 3. The horizontal bidirectional input was adopted, and the acceleration peak value was 0.85g, which corresponded to the extreme safety ground motion peak value of the prototype structure.

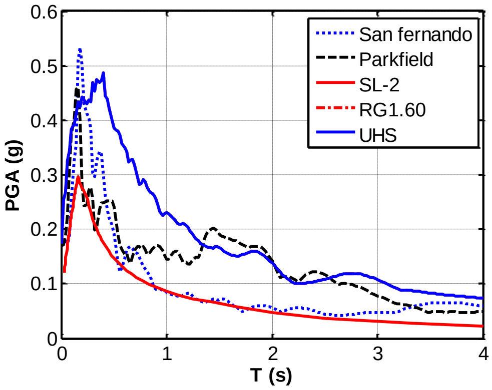
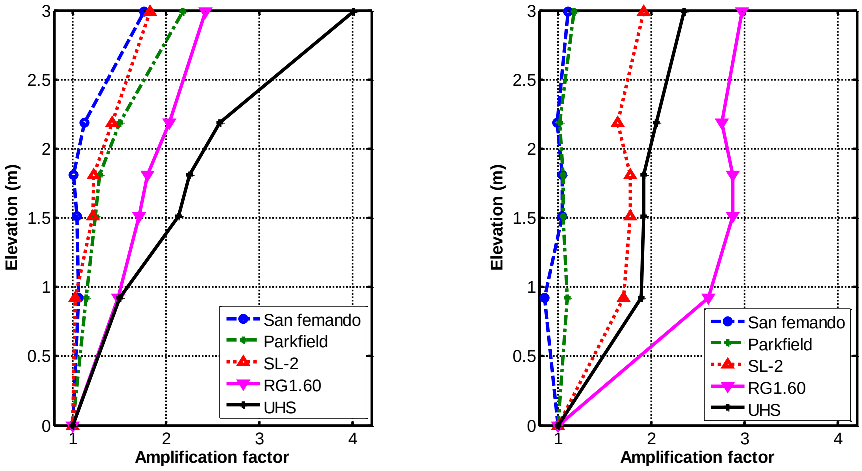


Fig.3 Seismic wave response spectrum

3 Results and discussion

3.1 Acceleration magnification factors

The acceleration magnification factors in the two directions of the structure are shown in Figure 4. Due to the large overall stiffness of the structure, the acceleration between floors is slightly increased. While the top floor is the workshop hall, with a large span and high headroom, which makes the acceleration of the roof amplification more significant, and there is a significant "whiplash effect".

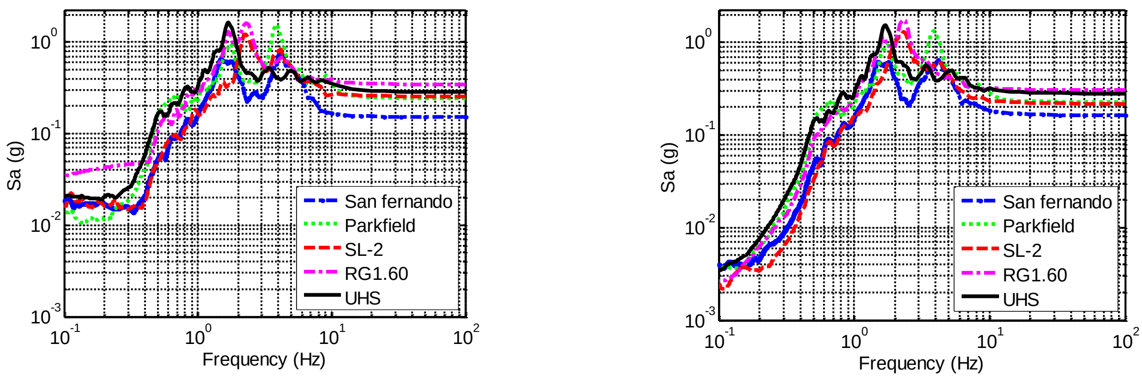


(a) (b)

Fig. 4 Acceleration amplification factors. (a) x direction; (b) y direction.

3.2 Floor response spectrum

The safety of nuclear power equipment is critical to the safe operation of the entire nuclear power system. The floor response spectrum at the equipment support can be used for safety analysis of the equipment. In this paper, the horizontal floor response spectrum was converted to the prototype for comparison based on similar relations, as shown in Figure 5. The peak frequency of the structure ranged from 1 to 5 Hz. The floor response spectra obtained by the two natural waves showed obvious double peaks, which were near 1Hz and 3Hz, respectively. The floor response spectrum obtained by the three artificial waves is dominated by a single peak. The peak floor response spectrum obtained by UHS appeared at 1.7Hz, while the peak of the floor response spectrum obtained from the SL-2 spectrum and the RG1.60 spectrum was slightly behind, and was located at 2.4Hz. The frequency of nuclear power equipment is mainly distributed after 7 Hz. The acceleration amplitude of the floor response spectrum obtained in the two directions of UHS was larger after 7Hz. the acceleration amplitude obtained by UHS at zero period was slightly smaller than the acceleration amplitude obtained from the RG1.60 spectrum, and larger than the acceleration amplitude obtained from other response spectra. UHS and RG1.60 spectrum have a great impact on the equipment, which should be fully considered in seismic design.



(a) (b)

Fig. 5 Floor response spectrum (Converted to prototype). (a) x direction; (b) y direction.

3.3 Displacement response

Fig.6 shows the displacement peaks at the top of the reactor plant obtained from different seismic wave inputs. It can be seen from Fig. 6 that under the same seismic wave excitation, the peak value in the y-direction is greater than the x-direction. This is because the structural stiffness in the y-axis direction is less than that in the x-axis direction, and the top-level displacement of the y-axis is more obvious. Among the displacements obtained by the 5 seismic waves, the displacement peaks obtained by the SL-2 seismic wave were the smallest. RG1.60 and UHS had a large displacement peak. The displacement in the x direction obtained by UHS was 1.07mm, which was 1.65 times larger than the displacement obtained in SL-2, which was 0.65mm. In the y direction, the displacement obtained by UHS was 2.23mm, which was twice the displacement obtained by SL-2.

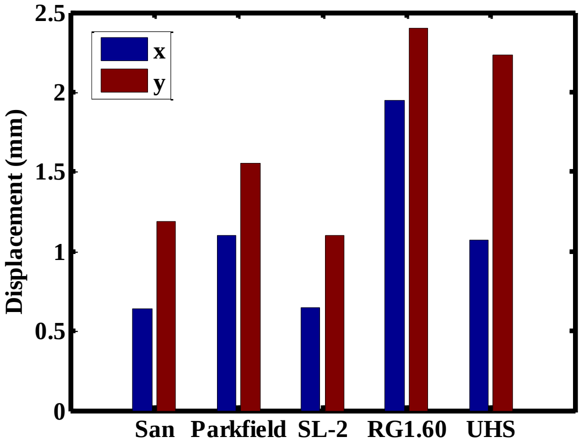


Fig. 6 Displacement peak at the top of the reactor plant

3.4 Model status

The peak acceleration input from the shaking table was gradually increased from 0.85g to 1.8g. No damage was found on the external wall of the model after the earthquake. The model was cut to observe the internal structural state, as shown in Fig. 7. There were no cracks in all parts of the interior, indicating that the nuclear power plant has excellent seismic performance.

(a) (b)

Fig. 7 Model profile. (a) Overall profile; (b) Pressure vessel exterior wall.

4 Conclusion

A 1:20 scale model NPP was designed on the basis of similitude law. Five seismic waves were used to stimulate the model. The results of shaking table tests show that the maximum acceleration amplification factor is 4. Meanwhile, the maximum relative displacement is 2.4. There are not obvious cracks on the surface of the scaled NPP after exceed design ground motion input. It is indicated that NPP has a good seismic behavior.

5 Acknowledgements

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6. References

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