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Shaking table model tests of concrete containment vessel (CCV) for CPR1000 nuclear power plant

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A B S T R A C T

Containment vessel of nuclear power plant is the last barrier to prevent the leakage of radioactive materials, so the seismic performance is of high importance. In order to investigate the seismic performance of the CPR1000 prestressed concrete containment vessel (PCCV) structure under design and beyond-design basis earthquake, a 1/20 scale concrete containment vessel (CCV) model was designed and constructed on the shaking table based on the similitude requirements from the Buckingham's π-Theorem. The horizontal and vertical earthquake waves generated from RG1.60 spectrum were selected as the input earthquake waves in the shaking table model test, and the earthquake waves with peak ground acceleration (PGA) 0.2*g*, 0.3*g*, 0.4*g*, 0.5*g*, 0.7*g*, 0.9*g* and 1.2*g* respectively were loaded step by step until the macroscopic failure occurred in the model containment vessel. The dynamic responses of the model CCV were obtained from the acceleration sensors and resistance strain gages. The model test results showed that the maximum acceleration magnification factor of the model CCV was 1.974 with PGA of 0.2*g*, which indicated that the CCV had a good seismic-resistant behavior under 0.2*g* earthquake. Until the second last test case with the horizontal peak earthquake motion of 0.9*g* (corresponding to 0.9*g* for the prototype structure), the fundamental frequency of the model CCV only decreased slightly and the maximum tensile strains at all monitoring points were much smaller than the ultimate tensile strain. It meant that the model CCV as a whole was within the elastic range. In the last case (1.2*g*), the model fundamental frequency decreased steeply. At the same time, the maximum tensile strains at the heel of the cylinder wall far exceeded the ultimate tensile strain and a circle of cracks occurred at the cylinder wall heel. It meant rupture failure had occurred and the cylinder wall heel of the CCV was the weak region. It agreed well with the numerical analysis results and the visual inspection and camera record at the test site. Although a circle of concrete cracks appeared around the cylinder wall foot, the model CCV still remained integral as a whole and neither cracking parts dislocation nor collapse occurred. Because the test model was a plain concrete structure and the model test results should be conservative estimation, it can be concluded that the prototype PCCV for CPR1000 nuclear power plant had sufficient seismic safety margin.

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1. Introduction

Containment vessel is an important structure in nuclear power plant and the last barrier to prevent the leakage of radioactive materials (Duan et al., 2014). When accident conditions occur, the containment vessel should be able to confine the radioactive materials inside. Otherwise the radioactive materials will leak out and seriously threaten people's life and property security. On March 11, 2011, the strongest recorded earthquake with a magnitude of 9.0 Megawatt (Mw) occurred in Japan, which triggered a powerful tsunami and caused a nuclear accident in one of the world's biggest nuclear power stations - the Fukushima Daiichi Nuclear Power Plant. The tsunami arrived at the plant station around 50 min after the initial earthquake. The 14 m high tsunami overwhelmed the plant's seawalls and damaged cooling systems and control rooms. Three out of the six reactors (units 1, 3 and 4) suffered hydrogen explosions from March 12 to March 15, 2011. Level 7 meltdowns occurred leading to large amount of radioactivity releases into the environment and causing widespread contamination with serious health and environmental effects (Bachev, 2014). The nuclear

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Notation

a	acceleration
E	Young's modulus
f	fundamental frequency
f_t	tensile strength
g	gravitational acceleration
L	length
m	model subscript
p	prototype subscript
t	time
u	displacement
v	velocity
X, Y	horizontal X and Y axes of the containment vessel
Z	vertical central axis of the containment vessel
σ	stress
ρ	density
ω	circular frequency
λ	similarity ratio
λ_a	acceleration scale
λ_E	Young's modulus scale
λ_f	fundamental frequency scale
λ_{ft}	tensile strength scale
λ_g	gravitational acceleration scale
λ_L	length scale
λ_t	time scale
λ_u	deformation scale
λ_v	velocity scale
λ_σ	stress scale
λ_ρ	density scale
λ_ω	circular frequency scale

accident triggered nuclear panic around the world, and the scholars of every country began to pay much attention to the safety of nuclear power plants under extreme disaster conditions. China is located between two large earthquake belts (Circum-Pacific seismic belt and the Eurasian seismic belt) and its earthquake fault zone is very active. So in order to ensure the safety of nuclear power plant, it has great significance to investigate the structural integrity and soundness of containment vessel under the design basis earthquake, and beyond-design basis earthquake.

Model tests and numerical simulation analyses are two main ways to study the seismic performance of containment vessel.

In terms of model tests, Qian et al. (2007) verified the seismic safety of the prestressed 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. The artificial earthquake waves with three peak accelerations of 1.0g, 2.0g and 3.0g, respectively, corresponding to 0.1g, 0.2g and 0.3g for the prototype PCCV structure, were employed as the input. The test results indicated that under an earthquake excitation with peak acceleration of 2.0g (corresponding to the design earthquake level SL-2, 0.2g for the prototype PCCV structure), the tensile strain at some concrete monitoring points near the fixed bottom of the model reached cracking level. When the peak acceleration was 3.0g, a small quantity of cracks appeared near the fixed bottom of the model, which meant the bottom part was the weak region in earthquake. Wang et al. (2013) 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 (peak acceleration 0.25g). The reason why the design earthquake level SL-2 is different from Qian et al. (2007) is because the research objects between them are different containment vessel structures. Three load cases of 0.1g, 0.2g and 0.3g peak accelerations (corresponding to 0.088g, 0.175g and 0.263g for the prototype containment) were applied. The third load case is equivalent to the design earthquake level of SL-2. The test results showed that the prototype containment was within the elastic range and had sufficient seismic safety margin under the seismic motion at the SL-2 level. Chen et al. (2014) constructed a scaled-down RCCV structure of advanced boiling water reactor (ABWR) for seismic test on the shaking table and also built the finite element model of RCCV by SAP2000 to calculate the dynamic responses numerically. The responses, such as the associated spectral acceleration, time histories of acceleration and of displacement, between experiment and numerical model agreed well with each other. Only some very tiny cracks were detected on the model RCCV under 0.4g earthquake, which do not affect the function of RCCV. In Japan, the Nuclear Power Engineering Corporation (NUPEC), conducted a series of shaking table tests for 1/8 scaled model RCCV with liner plate to validate the seismic design and reliability with a sufficient margin even under destructive earthquakes of a prototype RCCV used in the latest ABWR. The maximum design earthquake (S_1) with the horizontal maximum acceleration of 0.286g and the extreme design earthquake (S_2) with the horizontal maximum acceleration of 0.407g were employed as the input for the design level tests. The integer multiples of the horizontal S_2 waves (2–5 and 9 times S_2(H)) were used as the input for the safety margin tests. The test results, including the transition of the model's stiffness, natural frequencies and damping factors were given. The effects of vertical input motions and internal pressure on the model's characteristics and behavior, the load-deformation, the ultimate strength, the failure mode of the reinforced concrete portion and the liner plate were discussed. The model was still sound without any crucial damage until under 5S_2(H) test, and the leak-proof function of the liner plate was sound as well. The seismic safety margin was evaluated from the energy input during the failure test to a design basis earthquake. The pressure and leak tests were also carried out to confirm the structural integrity and leak-tight-proof function soundness of the RCCV (Hirama et al., 2005a, 2005b, 2007).

With the rapid advances in computation techniques in recent years, nonlinear finite element method became an important alternative approach to analyze concrete containment vessels' (CCVs') seismic response and cracking damage. Duan et al. (2014) carried out nonlinear static analysis and nonlinear time history analysis of a 1:10 scale unbonded PCCV structure with MSC. MARC finite element program to evaluate the behavior of the advanced unbonded PCCV for one typical China nuclear power plant under Japan's March 11 earthquake. The responses of the scaled model subjected to Japan's March 11 earthquake with the peak ground accelerations (PGA) of 0.781 g and 0.982 g were predicted by the dynamic analysis. The dynamic nonlinear analysis results showed fair agreement with the measurements of the pseudo-dynamic tests (Qian et al., 2007). Yi et al. (2016a; 2016b) established the finite element model of PCCV for CPR1000 nuclear power plant by ANSYS software, and analyzed the failure mechanism of the containment vessel under earthquake and internal pressure. The analysis results showed that the area around the equipment hatch was the weak region under internal pressure and the heel of the

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