EXPERIMENTAL STUDY OF SEISMIC FAILURE MODES OF HIGH-RISE INTAKE TOWERS

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Abstract

According to the investigation and analysis of earthquake damage, the seismic safety and proper functioning of intake towers including their hoist chambers immediately after an earthquake have been a matter of great concern. Dynamic response of hoist chambers is an important index to evaluate the seismic performance of the intake towers. Therefore, in this paper the failure pattern and mechanism of the whole system of intake tower-hoist chamber during earthquake was studied by shaking table experiment. On the basis of the similitude law, simulated concrete was used for small-scale intake tower test. The backfill concrete and rigid foundation system were considered in the test. The digital image correlation combined with traditional measuring and testing technique was applied. The whole process of intake tower system form elastic deformation, damage, to failure in incremental levels of Peak Ground Acceleration was investigated.

Keywords: hydraulic structures, intake towers, shaking table experiment, seismic response, failure pattern

1. Introduction

Intake towers form the entrance to the reservoir spillway or diversion system and are widely applied in water conservancy and hydropower projects for their good adaptation to the terrain condition, thus play a key role in the seismic resistance and safety of the whole project. As the development of the hydropower projects in meizoseismal area in southwestern China, a batch of hydropower project has entered the stage of design, some already under construction [1]. The seismic design of several high-rise intake towers is beyond the scope of current engineering experience [2]. And in recent years, with the increasement of the reservoir storage and dam height, the designed height of the intake towers has been more and more. The intake towers in Baihetan, Jinping, laxiwa, Wudongde and Lianghekou hydropower stations are more than one hundred meters high [3]. The height-width ratio of intake towers is also increasing, thus the towering characteristic is fairly obvious. Therefore, under serious challenges of seismic safety, it is crucial to study the seismic performance and capability of the high-rise intake towers.

The present researches on hydraulic structral dynamic model experiments mainly focus on water retainning structures, such as arch dams [4, 5] , gravity dams [6] and earth dams. In this paper the failure pattern and mechanism of the whole system of an intake tower-hoist chamber during earthquake was studied by shaking table experiment. On the basis of the similitude law, simulated concrete was used for small-scale intake tower test. The backfill concrete and rigid foundation system were considered in the test. The digital image correlation combined with traditional measuring and testing technique was applied. The whole process of intake tower system from elastic deformation, damage, to failure in incremental levels of peak ground acceleration was investigated.

2. General Description of the test

A high-rise intake tower of a hydropower station in southwest of China was selected as the representative experimental case. It is an underwater free-standing structure, where the height of the main tower and hoist chamber is 85.0 m and 19.5 m, the size of the cross section is 15×10.3 m, and the thickness of the tower is 2.2-2.9 m, respectively, as shown in Fig. 1.

The seismic design intensity is Ⅶ, and the horizontal peak ground acceleration (PGA) of the maximum design earthquake (MDE) and the maximum credible earthquake (MCE) is 0.1g and 0.25g, respectively. The horizontal time histories of ground motion acceleration were inputted in the experiment.

The shaking table is a three-direction and six-degree-of-freedom analogue-controlled system with a circular platform with a diameter of 5.75 m. The maximum payload is 20000 kg. The maximum acceleration, velocities, and displacement are 2.0 g, ±1000.0 mm/s and ±150.0 mm in horizontal directions, 1.33g, ±800.0 mm/s and ±100.0 mm in vertical directions, respectively. Its working frequency band is 0.1-100 Hz.

The geometry scale of the model was taken as 1/40. The maximum height of the model is 2.125 m. Because the effects of the backfill concrete cannot be ignored [7], a steel frame which could consider the dynamic interaction between the tower and backfill concrete was designed to connect the shaking table and the model. Fig. 2 shows the whole model system. The fundamental frequency of the connector is 71.42 Hz according to the numerical calculations, which can be considered to a rigid foundation.

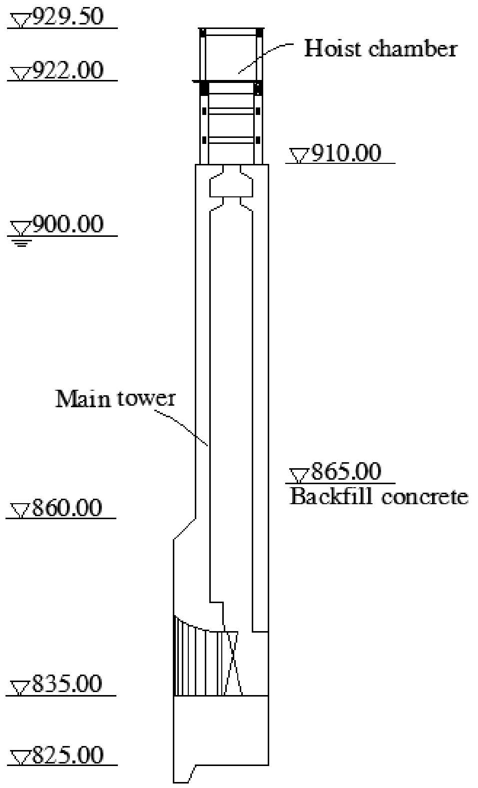


Fig. 1-Typical section of an intake tower (elevations in m above sea level)

Fig. 2-Model of the intake tower

Considering the follow-up experiment with the water condition, and because using water is the only rational selection of the liquid in the model reservoir, it is required that the density scale of the material and the acceleration scale must be in unity so that the hydrostatic pressure in a normal gravitational field can be correctly represented [8]. From geometry, density and acceleration scales, all scales of other qualities, such as time, stress, and others, can be determined according to the theory of complete similitude, in which the strain scale, a dimensionless quality, is unity. The scale of elastic modulus is 1/40. The scale of different qualities is shown in Table 1.

Table 1-The scale of different qualities

Scale of geometry *	$C_l = 40$
Scale of density*	$C_\rho = 1.0$
Scale of elastic modulus*	$C_E = 40$
Scale of acceleration*	$C_a = 1.0$
Scale of time	$C_t = C_l C_\sigma^{0.5} C_E^{-0.5} = (40)^{0.5} = 6.325$
Scale of frequency	$C_f = 1 / C_t = 0.158$
Scale of deformation	$C_\delta = C_t^2 C_a = 40$
Scale of strain	$C_\varepsilon = C_\delta C_l^{-1} = 1.0$
Scale of stress	$C_\sigma = 40$

3. Model material

Since one of the main purposes of the experiment was to examine the failure mode of the intake tower system under a strong earthquake, the nonlinear properties of the prototype structural concrete should be simulated. This required that the stress and strain relations of the model material and prototype concrete can be considered as a brittle material in tension, that is, when it reaches its yielding point the material loses tensile strength completely. Thus, it is possible to find a model material, because the stress and strain relationship of a brittle material can be represent by two straight lines [5]. Because the strength scale of the model was 1/40 in the experiment, the required tensile strength was 0.07 MPa to simulate structural concrete in age of 180 days with a tensile strength of 2.8 MPa. A novel simulated concrete were developed by mixture of water, cement, talcum powder and barite sand. The failure modes of the simulated concrete in four-point bend and compression testing were like the regular concrete, as shown in Fig. 3. The material parameter is listed in Table 2. However, it is clear that not all characteristics matched the similitude requirements, such as the Poisson ration and material damping, both very difficult to control. The rebar in the reinforced concrete was simulated by copper wire.

The whole model was constructed by two steps. In the first step, the main tower and the backfill concrete was integral concreting. When the concrete formwork inside the tower was removed, the hoist chamber was constructed.

Table 2 – The scale of different qualities

Material	Prototype structural concrete	Simulated model concrete
Density (kg/m^3)	2400	2479
Dynamic elastic modulus (MPa)	45000	1210
Static tensile strength (MPa)	2.8	0.072
Static compressive strength (MPa)	28.0	0.694

(a) Four-point bend testing

(b) Compression testing

Fig. 3-The failure mode of the simulated concrete in performance testing

4. Measuring techniques and data acquisition

A total of 84 contact channels of two types of data were measured, including accelerations and dynamic strains of the key positions in the main tower and the hoist chamber, as shown in Fig. 4. The sampling frequency of data acquisition of acceleration and strain was 1000 Hz and 500 Hz, respectively. And the non-contact measuring and testing techniques were applied in the experiment. The tree-dimensional digital image correlation (3D-DIC) technology was used to measrue the whole field strain and displacement of the structural upstream and side faces as shown in Fig. 5. Optotrak-Certus (OC) technolegy was uesd to measure the dynamic displacement of key positions on 7 marks. The sampling frequency of data acquisition of 3D-DIC and OC was 50 Hz and 500 Hz, respectively.

Fig. 4-The arrangement of acceleration sensors and strain gages

Fig. 5-The testing surfaces of 3D-DIC

5. Experimental results

5.1 Test program

As summarized in Table 3, totally 19 different cases of tests were carried out, including the design level, checking level and overloading inputs, and the excitations with the white noise of 0.05g, before and after every seismic input. In the design level, two different artificial accelerations and a measured ground motion records named Lander were inputted, respectively.

Table 3 – The scale of different qualities

case	Type of excitation	PGA (g)			Record Duration (s)		Load level
		Stream	Cross-stream	Vertical	Original Duration	Test Duration	
1	White noise	0.05	0.05	0.05	120		
2	Artificial acceleration 1	0.1	0.1		45	7.115	Design
3	Artificial acceleration 2	0.1	0.1		20	3.162	Design
4	Measured ground motion acceleration	0.135	0.130		40	6.324	Design
5	White noise	0.05	0.05	0.05	120		
6	Artificial acceleration 1	0.2	0.2		45	7.115	2 times
7	White noise	0.05	0.05	0.05	120		
8	Artificial acceleration 1	0.25	0.25		45	7.115	Checking
9	White noise	0.05	0.05	0.05	120		
10	Artificial acceleration 1	0.3	0.3		45	7.115	3 times
11	White noise	0.05	0.05	0.05	120		
12	Artificial acceleration 1	0.4	0.4		45	7.115	4 times
13	White noise	0.05	0.05	0.05	120		
14	Artificial acceleration 1	0.5	0.5		45	7.115	5 times
15	White noise	0.05	0.05	0.05	120		
16	Artificial acceleration 1	0.6	0.6		45	7.115	6 times
17	White noise	0.05	0.05	0.05	120		
18	Artificial acceleration 1	0.7	0.7		45	7.115	7 times
19	White noise	0.05	0.05	0.05	120		

5.2 Observed damage

The damage response of the intake tower model with increment of PGA is shown in Fig. 7 to 12. The key positions are shown in Fig. 6.

In Case 2 to 4, when PGA is in design earthquake level, no crack is observed in the main intake tower structure and hoist chamber.

In Case 6, when PGA= 0.2 g, no crack is observed in the main intake tower structure. For the hoist chamber, cracks initiate at lower main beams and upper main columns. And it is unchanged at the end of Case 8 in the check earthquake.

In Case 10, when PGA= 0.3 g, no crack is observed in the main intake tower structure. For the hoist chamber, cracks appear at the junctions between the lower main beams and columns, and the upper main beams and columns, respectively.

In Case 12, when PGA= 0.4 g, for the main intake tower, the through cracks are formed at the junction between the tower and backfill concrete; For the hoist chamber, the cracks at the junction between the lower and upper main beams and columns are developing and increasing, and some new cracks initiate at the junctions between the linking beams and lower main columns, and the bottom of the lower main columns.

In Case 14, when PGA= 0.5 g, for the main intake tower, the through cracks at the junction between the tower and backfill concrete has no obvious change. For the hoist chamber, some junctions between the lower and upper main beams and columns are nearly destructive. The cracks at the junction between the linking beams and lower main columns, and the bottom of the lower main columns are developing and increasing.

In Case 16, when PGA= 0.6 g, for the main intake tower, the through cracks at the junction between the tower and backfill concrete has no obvious change. For the hoist chamber, the all junctions between the beams and columns, and the lower main columns and tower top are destructive.

In Case 18, when PGA= 0.7 g, for the main intake tower, the whole tower is disconnected along the through cracks at the junction between the tower and backfill concrete. The whole hoist chamber is failure. One beam on the top of the hoist chamber is fallen.

The residual deformation of the model at the end of the expriment is shown in Fig. 13.

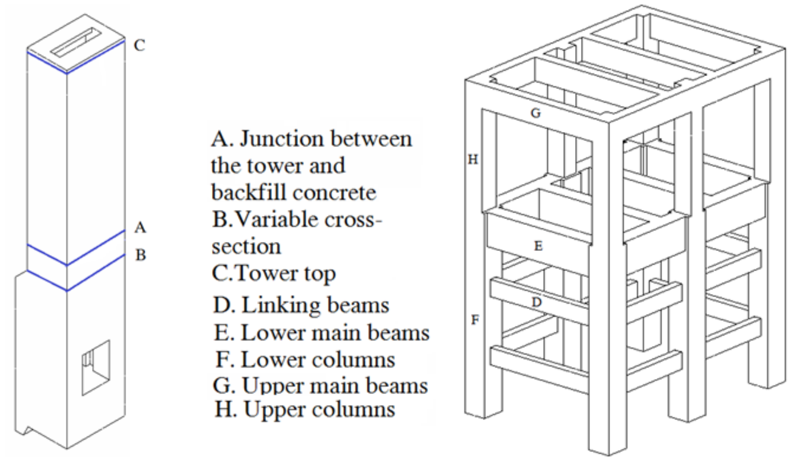
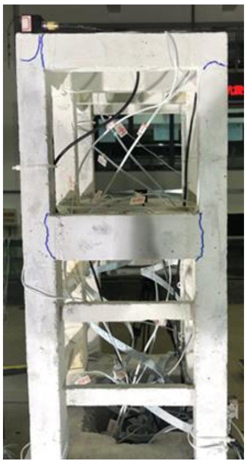


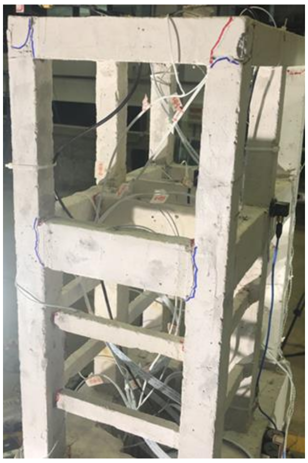
Fig. 6- Key positions

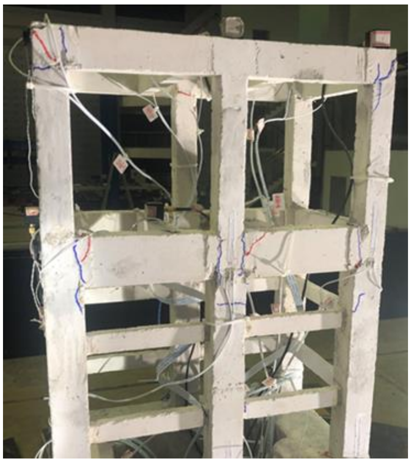
Fig. 7- Cracking response at PGA= 0.2 g


(a)


(b)

Fig. 8- Cracking response at PGA= 0.3 g


(a)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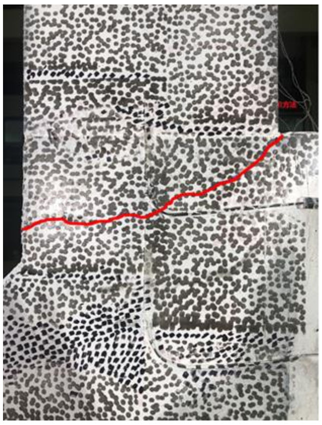

(c)

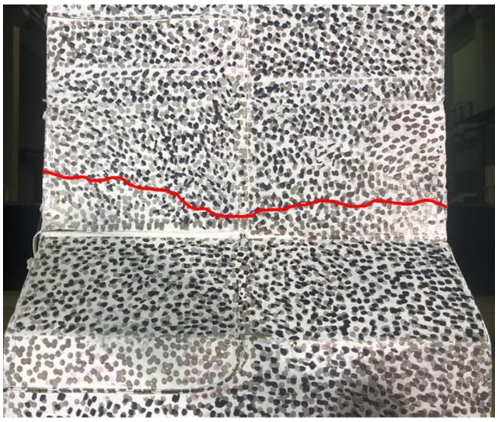
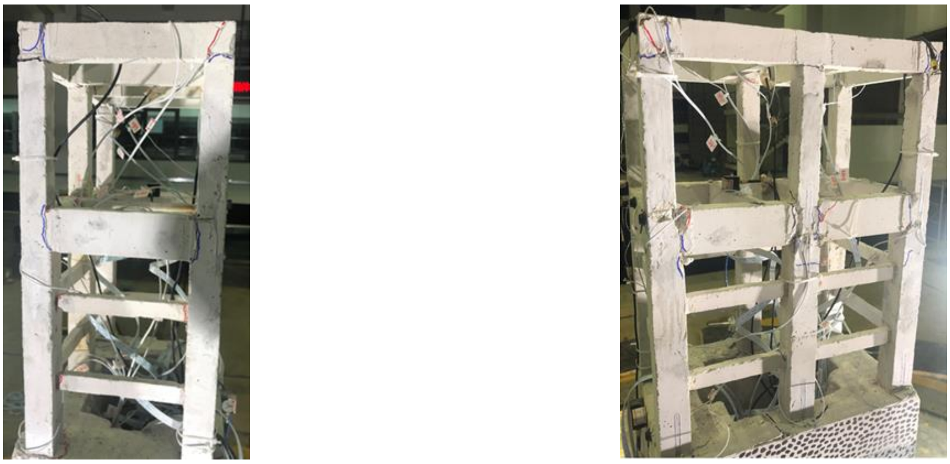

(d)

Fig. 9- Cracking response at PGA=0.4 g



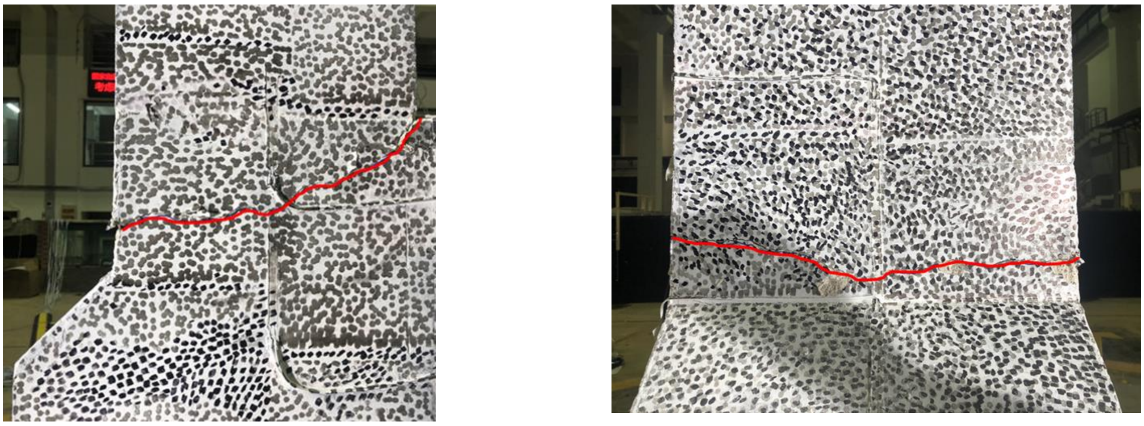
(a) (b)

Fig. 10 - Cracking response at PGA=0.5 g

(a) (b)

Fig. 11 - Cracking response at PGA=0.6 g

(a) (b)



(c) (d)

Fig. 12 - Cracking response at PGA=0.7 g

Fig. 13 – Residual deformation of the model at the end of the expriment

5.3 Seismic failure patterns

In summary, the model subjected to seismic loading mainly experiences cyclic tensile-compressive stress. However as the compressive strength is much larger than the tensile strength, the cracks are mainly tensile cracks However, the structure may not global failure immediately as it still could undertake shear forces. When it is close to global failure, the tensile cracks zones are formed.

The damage of the main tower structure mainly occurs at the junction between the tower and backfill concrete. The damage of the hoist chamber initiates at the junction of both ends of beams and the bottoms of the columns.

Therefore, a potential seismic failure pattern of the high-rise intake tower at shaking table experiment could be summarized. For the main tower structure, the cracks initiate the junction between the tower and backfill concrete and propagate from surface to inside; then the cracks initiate at the junction between the tower top and the hoist chamber. As the earthquake continues, the cracks at the junction between the tower and backfill concrete penetrate. The crack zone is a slope. The whole tower is disconnected.

For the hoist chamber, the seismic cracks initiate successively in the lower main beams, upper main beams upper columns, linking beams and lower columns, and develop from the main beams to the linking beams, and from the upper columns to the lower columns, respectively. The damage of the hoist chamber appears earlier and develops more quickly than that of the main structure.

6. Conclusion

(1) The seismic damage of the main tower structure mainly occurs at the junction between the tower and backfill concrete. The crack zone is a slope.

(2) The seismic damage of the hoist chamber initiates at the junctions of both ends of beams and the bottoms of the columns, and then the all junctions between the beams and columns are destructive. The damage of the hoist chamber appears earlier and develops more quickly than that of the main structure.

(3) At the end of the experiment, the whole tower is disconnected along the junction between the tower and backfill concrete. The hoist chamber is severe deformation and failure.

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