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STATIC-DYNAMIC ANALYSIS AND CRACKING MECHANISM STUDY ON THE SHAPAI RCC ARCH DAM IN THE MEIZOSEISMAL AREA

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ABSTRACT

The Shapai RCC arch dam, at 132m tall, is one of the tallest RCC arch dams in the world and was built at the end of 20th century. The dam was located in the meizoseismal area of the "5.12" Wenchuan Earthquake, merely 36km from the epicenter. The local seismic intensity was 9, far greater than the design intensity of 7. The Shapai arch dam suffered the excessive standard seismic load and survived the earthquake. The dam performed well without any noticeable damage, and the dam and foundation remained intact. Therefore, the Shapai arch dam became the world's tallest RCC arch dam to withstand the test of a massive earthquake. To summarize the characteristics of the seismic damage and the seismic experience, a method combining experimental investigation and numerical simulation is used in this paper to conduct a static and dynamic analysis of the Shapai RCC arch dam and the cracking mechanism. The research results can provide references for the safe construction and operation of similar hydraulic and hydroelectric projects in meizoseismal areas.

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The Shapai RCC arch dam, at 132m tall, is one of the tallest RCC arch dams in the world and was built at the end of 20th century. The dam was located in the meizoseismal area of the "5.12" Wenchuan Earthquake, merely 36km from the epicenter. The local seismic intensity was 9, far greater than the design intensity of 7. The Shapai arch dam suffered the excessive standard seismic load and survived the earthquake. The dam performed well without any noticeable damage, and the dam and foundation remained intact. Therefore, the Shapai arch dam became the world's tallest RCC arch dam to withstand the test of a massive earthquake. To summarize the characteristics of the seismic damage and the seismic experience, a method combining experimental investigation and numerical simulation is used in this paper to conduct a static and dynamic analysis of the Shapai RCC arch dam and the cracking mechanism. The research results can provide references for the safe construction and operation of similar hydraulic and hydroelectric projects in meizoseismal areas.

Introduction

The "5.12" Wenchuan Earthquake was a rare and huge disaster to the epicenter and the surrounding areas. Nearly 30% of the dams in Sichuan province sustained some degree of damage, and approximately 20% of those dams were at high risk of dam-break danger, which seriously affected the project operation and endangered the safety and property of people living downstream of the dams. This disaster challenged researchers with unprecedented hydraulic and hydroelectric projects in earthquake zones. Targeted, in-depth research of dam safety in the meizoseismal area is very urgent. The instructive reference for the safe construction and operation of hydraulic and hydroelectric projects in meizoseismal area must be provided[1].

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As a typical concrete arch dam in high seismic intensity region, the Shapai hydropower station has a complicated topography and geological conditions. The structure of the dam is complex. In the “5.12” Wenchuan Earthquake, the Shapai arch dam became the tallest RCC arch dam in the world to withstand an earthquake. Therefore, it is necessary to research the operating state of the Shapai arch dam and summarize the characteristics of the earthquake damage and anti-seismic experience.

Abstract of the Shapai Project

General Layout of the Shapai Project

The Shapai hydropower station is located in Wenchuan County, Aba Prefecture, Sichuan Province and is a step leading power station in upstream Caopo River, a tributary of the Minjiang River. The pivotal project consists of an RCC arch dam, two spillway tunnels, conduit tunnels, a powerhouse and other buildings (dam site layout shown in Fig.1). The Shapai arch dam is 132m tall and is the tallest arch dam in the world built by China at the end of the last century. The dam has a crest height of 1867.5m, a normal water level of 1866m, a total capacity of 18 million m^3, and an installed capacity of 36MW.

The water retaining structure of the Shapai project is a three center RCC gravity-arch dam with a maximum height of 132m, a crown thickness of 9.5m, a crown cantilever bottom thickness of 28m, and a thickness-to-height ratio of 0.238. The crest centerline arc length is 250.25m, the largest central angle is 92.48 °, the camber ratio is 2.13, and the dam volume is 383 000m^3. The main arch geometric parameters are shown in Table 1, and the arch dam figure is shown in Fig.2.

The Geological Conditions and Ground Motion Parameters of the Shapai RCC Arch Dam

The dam base of the project is made of granodiorite mixed with epidote, biotite and quartz hornfels, with no fault development along the river; therefore, the dam base has no influence on the stability of the dam, except for partial treatment. The dam abutment resisting force body are stable overall, but the arch ring above ▽1840m has schist (Sc) with poor bearing capacity, and the abutment rocks appear to be thin and in need of engineering treatment.

Regarding the seismic fortification criteria of the Shapai hydropower station, the basic seismic intensity at the construction period is determined to be 7. According to the probability analysis, the seismic intensity of the dam site with a 10% exceeding probability in 50 years is 7.4 and the acceleration of the earthquake peak is 0.137g; the acceleration of the horizontal design peak corresponding to a 2% exceeding probability in 100 years is 0.280g. The main results of the seismic hazard analysis are shown in Table 2. A seismic safety evaluation and a review of the Shapai hydropower station engineering site were conducted after the Wenchuan earthquake. Based on the research, the newly approved results of the probabilistic seismic hazard analysis of the Shapai hydropower station after the "5.12" earthquake are shown in Table 3[2].

The Influence of the Wenchuan Earthquake on the Shapai Project

Before the earthquake, the water level of the reservoir is close to the normal level, the two spillway gates are closed, and the power units are fully running. After the earthquake, we can see through aerial photos and on-site inspection that the appearance of the RCC arch dam is in good condition, without any damage, and the abutment resisting force body is stable, with only partial superficial rocks lifted or slipping. The terrain near the banks of reservoir and dam and the slope on both banks of the visible reservoir area are complete with lush vegetation, and no large-scale landslides are observed. The dam has undergone the test of Wenchuan M8 earthquake and several aftershocks. The earthquake had a great impact on other buildings. In the outbuildings of the dam, the filler wall of the operating room of the dam elevator shaft has cracked, the bent frame columns of the water intake hoist have crazed, the left bellows of the river-crossing pipe bridge of the guide water steel pipe have been broken, the high pressure water is jetting, and the main and assistant powerhouses are flooded, as are the power units and other equipment. The structures of the main and assistant powerhouses are seriously damaged near the mountain by the flying rocks, and the bridge crane in the plant is smashed and has collapsed. The side slope of the surge shaft has collapsed, many incoming roads have caved in, and the plant has been seriously damaged. However, the two spillway gates can still open normally, and one of them is opened to release water so that the water level can decrease gradually. Photos 1, 2, and 3 show the Shapai dam after the earthquake[3-4].

When the water level has dropped to approximately 1806m, several examinations are conducted on the upstream and downstream dam surfaces. A crack that is several meters long is found at the top of right cross joint of the upstream dam surface, but no corresponding crack at the cross joint of dam crest is observed. No other cracks have been found on the dam surface and in the gallery of the dam.

The Geomechanical Model Experimental Study of the Shapai Arch Dam

During the construction period of the Shapai arch dam, to study the overall stability of the dam and the foundation of the RCC arch dam under normal load combinations, we use an integrated geomechanical model test method to analyze the stability of the dam abutment, to comprehensively analyze and evaluate its safety, and to make suggestions about the scope and methods of the reinforcement of the dam abutment[5-7].

The Geometric Scale Ratio and Simulation Range of the Model

The geometric scale ratio of the model is $C_l = 200$. According to the topography, geology, project layout and other characteristics of the dam site, and the key demands of the study, the simulation range of model is determined to equal to the prototype size 300 × 400m^2 (vertical × horizontal). The model base is $\bigtriangledown$1644.5m; the depth from the bottom surface of the pedestal to the base plane of the model is 45.5cm in total, more than two thirds of the dam height.

Model Material and Its Mechanics Parameters

Refer to the physical mechanical parameters of the rock mass material of the Shapai RCC arch dam model, the dam body and rock mass model materials are developed.

The rock mass material uses the geomechanical model test material, which has a high density, low modulus and low strength and is made with different proportions according to the different requirements of the tests. The material is pressured into blocks of different sizes by the press machine for the standby application.

The main purpose of this test is to explore the process, form and failure mechanism of the instability of the abutment damage. Therefore, the dam body is made from a plaster casting system because it is only considered as a power transmission mechanism.

Loading and Measurement System

Under normal operation conditions, the Shapai RCC arch dam mainly bears loads such as the dam body weight, water pressure, silt pressure, and temperature. The temperature load will not be included in this test.

To obtain the deformation characteristics of different areas of the dam and the dam abutment, 11 displacement measuring points are arranged on three typical elevations on the downstream of the dam body surface, and 34 displacement measuring points are arranged along the contour lines of the two abutments. Additionally, 9 groups of strain rosettes are arranged on the typical elevation of the downstream dam surface, and 6 groups are arranged on the upstream dam surface.

Considerations of Model Loading Method

There are three research methods for the geomechanical model test: the overloading method, the strength reduction method and the synthetic method. The overloading method is currently commonly used, is relatively easy and is equipped to synch with the current specifications. However, the overloading method is a single-factor method. The synthetic method is the combination of the overloading method and the strength reduction method, and it can reflect the real situation of engineering in the global stability of dam and foundation research. This test first employs overload, which is four times the normal load, and then maintains this load to incrementally heat the two abutments and the resistance body parts of the rock mass until the instable loading program is destroyed.

Experimental Results and Analysis

The stress state of the dam body is well under normal pressure loads. The water-density-exceeding method will be applied, and the water load will be increased continuously. When the pressure overloads 2.6 times the normal pressure, cracks begin to appear on the arch dam. When the pressure reaches 4.3 times the normal pressure, the left bank cracks horizontally at 1796 meters elevation and has a trend of shearing out, the downstream arch abutment at 1820 meters elevation cracks lateral horizontally, and the upstream arch abutment at 1830 meters elevation cracks and develops downwards. On the right bank, the upstream arch abutment at 1830-1810 meters elevation cracks, the downstream slope arch abutment at 1824 meters shears out at approximately 30cm, the 1810 meters elevation cracks horizontally to the ridge, the 1800 meters elevation shears out horizontally and the downstream arch abutment at 1810 meters elevation is fractured for approximately 5cm. Finally, when the pressure reaches 8.2 times the normal pressure, many long and large cracks appear on the arch dam’s upstream and downstream surface, and the entire resistance of body cracks. Photos 4, 5, and 6 show the failure mode of the

Shapai dam.

The figures show that the crack initiation's overload safety coefficient is approximately 2.5, the large deformation's overload safety coefficient is approximately 4.0 and the ultimate bearing capacity factor of safety is approximately 8.0. Thus, the Shapai arch dam has a high overload degree of safety.

Regarding the abutment failure pattern, the right bank above 1810 meters, especially the upper ridge and the gully parts, and the left bank above 1820 meters, especially the steep rock parts of the downstream abutment, are badly damaged. Therefore, these two parts need to be reinforced. According to the analysis of the form and depth of the damages in the internal part of the abutment, the use of pre-stress anchor cable reinforcement is beneficial, and the suitable depth is 35-40 cm. The engineering adopted the recommended strengthening plan, and according to the earthquake damage from the Wenchuan earthquake, the abutment, which is reinforced by the ejector anchor and pre-stress anchor cable, has not been damaged at all, and the safety of the dam is effectively guaranteed.

The Post-earthquake Dynamic Stability Review of the Shapai Arch Dam and the Ground-based System

During the "5.12" Wenchuan earthquake, the Shapai arch dam became the tallest RCC arch dam in the world to withstand an earthquake. The post-earthquake dynamic characteristics and seismic performance of the dam can influence the safety of the engineering's long-term operation. Therefore, the post-earthquake operating state of the Shapai arch dam should be studied, making use of the results of the simulation analysis of the numerical model to systematically analyze the working conditions of the post-earthquake dam, the law of the factors that influence the seismic capability of the arch dam, as well as the influential degree, the limited earthquake resistance capability and the stability status under the condition of dynamics to form comprehensive reinforcement measures of the dam[8-10].

Static and Dynamic Finite Element Calculation Model of the Arch Dam

To fully reflect the valley terrain and the abutments (basements) rigidity and their influences on the deformation and stress distribution characteristics of the Shapai arch dam, a scope of abutment (basement) and dam body will be chosen to establish a three-dimensional nonlinear finite element model. See detailed information in Figs. 3 and 4.

The calculation ranges involve lithologies, such as the granite, phyllite and weak tectonic belt Sc. Eight node parameter entity units will be adopted when the dam body and abutment (basement) rock mass is dispersed. The inducing joints and cross joints will adopt contact units for simulation. The calculation range will be dispersed into 9863 nodes and 8750 units.

Operating Condition Calculation and Results Analysis

A three-dimensional, nonlinear, static and dynamic finite element method will be adopted, and the following 3 operating conditions will be reviewed on the basis of the results of the earthquake risk probability analysis of the Shapai hydropower station's engineering site after the

Wenchuan earthquake:

Operating condition 1: 50 years' exceedance probability, 10%, a_h=0.205 g.

Operating condition 2: 100 years' exceedance probability, 2%， a_h=0.452 g.

Operating condition 3: 100 years' exceedance probability, 1%, a_h=0.531 g.

The maximum dynamic response (dynamic displacement and dynamic stress) of the dam body and the abutment, as well as the safety factor of the abutment rock mass points, will be obtained through these three operating conditions. The damage-cracking characteristics of the dam body, the inducing joints and the cross joints are researched. The possible unstable parts and unstable mode of the dam body are revealed. The dynamic characteristics and limited aseismic ability of the concrete Shapai hydropower station arch dam are evaluated. At the same time, the reasonable comprehensive reinforcement measures of the dam basement and body are proposed. The main research results and suggestions are as follows:

（1）Under operating condition 1, there were only a small amount of tensile ruptures or plastic damage on the upstream right arch at 1780-1810 meters elevation and the downstream left arch at 1867.5 meters elevation. The damage is minimal, and the overall operating condition of the dam is good.

（2）Under operating condition 2, the whole dam body will be stable. Under operating condition 3, the whole dam body will be stable except the perfoliate plastic damage, which appears at the left arch elevation, inducing the joint and cross joint of the dam top in approximately 50.0 meters scope.

（3）Under these three operating conditions, the safety factor of the abutment, as well as the basement, would reduce gradually with the increase of the earthquake magnitude, but would remain above 1.1. Only when the earthquake operating condition is met, which occurs once every ten thousand years, the right and left shallow or surface parts of the abutments will tend to the sliding state.

（4）The two inducing joints and cross joints were not damaged at all under operating conditions 1 and 2, and there was only partial or perforating damage on the left arch elevation under operating condition 3.

（5）Based on the above analysis, it is suggested that detection of the left arch elevation, the inducing joint and cross joint should be reinforced after the great earthquake, and the grouting reinforcement processing should be conducted. Appropriate rebar could be configured at the plastic yield area of the dam body when necessary, and reinforcement measures of the shallow or surface rock mass, which may lose its stability at the abutment, should be taken. Additionally, it is suggested that the survey of the transformation and cracking of the dam body, abutment and basement should be enhanced to address the problems appearing over time to ensure the safety of the engineering.

Conclusions

With a reasonable structural design, high stability, great overload capacity and super anti-seismic potential, the batholith geological condition of the Shapai arch dam is preferable overall. The May 12th great Wenchuan earthquake greatly influenced the dam site, but the appearance of the dam is good, and there is no obvious damage, demonstrating that the dam can bear the effects of an earthquake and has a super anti-seismic capability. The Shapai arch dam can still be used to retain water as a standard task.

According to the preliminary review analysis of the earthquake resistance safety of the Shapai arch dam, the dam has a huge potential in resisting earthquakes. Namely, the current design theory and method of the dam can guarantee the safety of the dam. However, in-depth research should be conducted if we want to grasp the real earthquake resistance potential of the arch dam.

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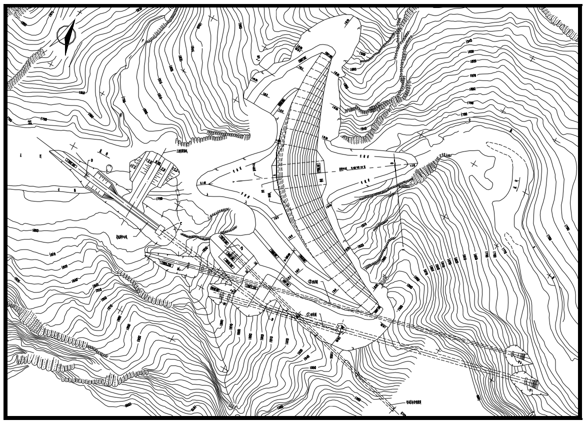

Figure 1. Head junction of the arch site

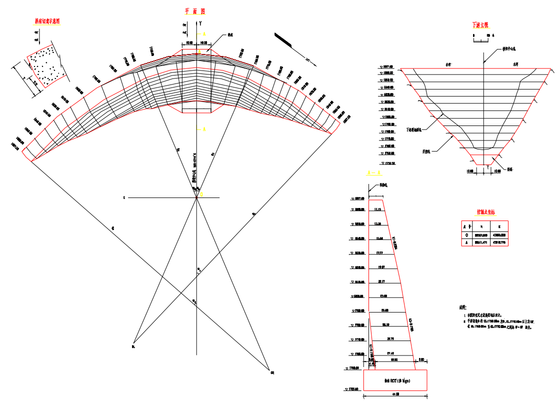

Figure 2. Body shaping of the arch dam

Table 1. Geometric parameters of the arch dam

Items	Characteristic parameter	Items	Characteristic parameter
Crest elevation（m）	1867.5	Thickness-height ratio	0.238
Height of dam（m）	132.0	Arc height ratio	2.130
The thickness of the dam crest（m）	9.5	The volume of the dam（$10^4 m^3$）	35.80
Thickness of the dam bottom（m）	28.0	The volume of the pedestal（$10^4 m^3$）	2.5
length of the arch axis arc（m）	250.25	Foundation excavation（$10^4 m^3$）	58.20

Table 2. The results of the seismic hazard analysis of the Shapai Project before Wenchuan earthquake

Time limits		Exceedance probability in 50 years				Exceedance probability in 100 years
Exceedance probability		0.63	0.10	0.05	0.03	0.02
Seismic intensity	Damsite	6.2	7.4	7.7	7.9	8.3
	The site of the factory	6.2	7.5	7.8	8.0	8.4
The peak acceleration of bedrock (g)	Damsite	0.0509	0.1375	0.1729	0.2026	0.2803
	The site of the factory	0.0531	0.1543	0.1973	0.2353	0.3250

Table 3. The results of the seismic hazard analysis of the Shapai Project after Wenchuan earthquake

Time limits		Exceedance probability in 50 years				Exceedance probability in 100 years	
Exceedance probability		63%	10%	5%	3%	2%	1%
Seismic intensity	Damsite		8.1	8.5		9.4	9.6
	The site of the factory	6.5	8.1		8.9		

The peak acceleration of bedrock (g)	Damsite		0.205	0.282		0.452	0.531
	The site of the factory	65	0.518		0.356		

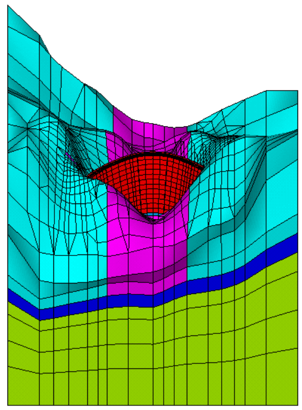

Figure 3. Three-dimensional nonlinear finite element model of the Shapai project

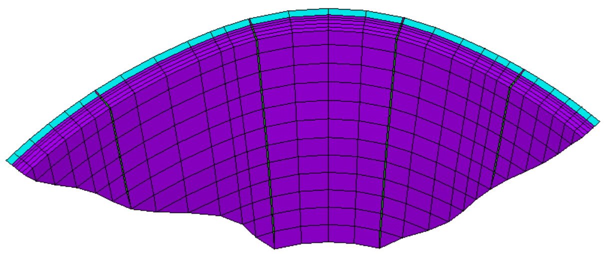

Figure 4. Three-dimensional nonlinear finite element model of the Shapai RCC arch dam

Photo 1. Little earthquake damage of the Shapai RCC arch dam after after Wenchuan earthquake

Photo 2. Dam abutment resisting force body is almost well after Wenchuan earthquake

Photo 3. The earthquake damage of the powerhouse

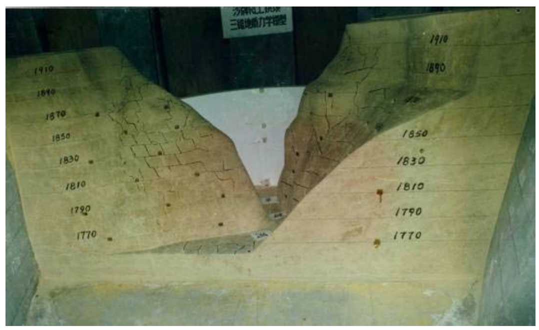

Photo 4. The failure mode of the model from Downstream

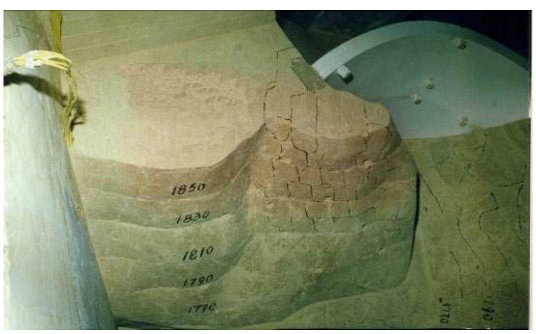

Photo 5. The failure mode of right abutment

Photo 6. The failure mode of left abutment