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CHALLENGE IN THE STUDY OF ULTIMATE CAPACITY OF HIGH ARCH DAMS UNDER EARTHQUAKES

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ABSTRACT

Many high arch dams are or will be under construction in the southwest area of China for the development of hydropower there. Their safety during earthquakes is a big concern and presents an inevitable challenge which has to be tackled with. The research works on the ultimate capacity of high arch dams against earthquakes are one of the key topics to prevent uncontrollable release of the water in reservoirs. Until now, very few dams have actually experienced ground shaking to be expected during the so-called safety evaluation earthquake, which is the basis for today's seismic design of dams. To study the ultimate capacity, both numerical methods and physical model tests can be employed, and the results from them can be verified and complemented with each other. Consequently, our knowledge about the ultimate capacity of arch dam systems can be more complete and more concrete. The results of the experimental studies on the damage of arch dams can be an important supplement to the scarce cases of the responses of arch dams during very strong earthquakes and provide useful data as well as visible evidence on the development of the damages which may be related to the final failures of arch dams.

INTRODUCTION

Dams are very important infrastructures for modern society, which store water for irrigation, domestic and industrial use, as well as power generation. However, the stored water may be a potential threat or even disaster to the residents and social properties downstream, if the reservoir were released out of control at some extreme circumstances. Extreme flood, geological movement at the dam site or reservoir and earthquake are the most possible events which may cause serious damage or even failure of the dams resulting in the uncontrolled release of the reservoir.

Dam safety during strong earthquake is a big concern for all dams in the seismically active regions. Until now, arch dams worldwide keep an excellent record during past earthquakes. No arch dam has been seriously damaged due to earthquake. However, it should be noted that seldom dams are located very close to the faults of the destructive earthquakes occurred in the past. This implied that rare arch dams have actually experienced ground shaking to be expected during the so-called safety evaluation earthquake. According to recent investigations, there are about 50 existing arch dams in 15 countries that have subjected strong earthquakes(FERC,1999, Wieland and Chen, 2009), but only 8 arch dams have experienced ground motion over or close to their design levels. They are Pacoima dam, Lower Crystal Springs dam and Gibraltar dam in the United States, Ambiesta dam in Italy, Shapai dam and Techi dam in China, Rapel Dam in Chile and Shin Toyone dam in Japan.

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It is very difficult to predict precisely earthquake ground motions for a structure in its life-cycle period. The return period as long as thousands of years in the seismic risk analysis is used to determine the design seismic loads, but the real earthquake ground motions may exceed the design level despite of very low probability of such an extreme event in an average sense. Therefore, to evaluate the ultimate capacity of an arch against earthquakes is one key element to prevent uncontrolled release of the reservoir. The most reliable criteria for the evaluation of ultimate capacity of a structure shall be based on the actual damage and failure modes during earthquakes as well as the data from the full scale test with structural components in the laboratory. However, the real data of arch dams under strong earthquakes are scarce and the criteria used in the design may not have a clear relation with the possible failure modes in the future.

The determination of the seismic ultimate capacity of an arch dam requires a full simulation of the process of damage development as well as the failure mode of the arch dam system including its foundation and reservoir. The model system used, no matter numerical or physical, must consist of the arch dam, partial foundation rock with topographic feature near the dam, rock wedges in contact with the dam and partial reservoir. The influence of the far field, which is not included in the limited model , should be treated properly to take into account the radiation of the dynamic energy to the infinite. Furthermore, various types of non-linearity, such as the contact between contraction joints, sliding of wedges and cracking of the concrete material, must be properly simulated.

Both numerical simulation and physical model test of arch dam systems have been conducted in recent years at China Institute of Water Resources and Hydropower Research (IWHR) to study the seismic responses as well as the seismic ultimate capacity (Tu et al., 2006, Wang and Li, 2006 and 2007). Table 1 lists the arch dams which have been investigated at IWHR. Of 305m in height, Jinping Stage I is the highest arch dam in the world. Daganshan arch dam of 210m in height has the largest design PGA for arch dams in China. The authors will summarize the main results of above arch dams in this paper and the tough problems in the study of the seismic ultimate capacity by either numerical simulation or physical model test.

Table 1. List of the arch dams been investigated

Dam Name	Dam Height (m)	Crest Length (m)	Reservoir Capacity (10^6m^3)	Installed Capacity (MW)	Design PGA (g)
Xiluodu	285.5	698.09	12670	13860	0.321
Xiaowan	292	922.74	14914	4200	0.313
Dagangshan	210	634.58	742	2600	0.557
Wudongde	265	320.21	7405	10200	0.270
Baihetan	289	709.90	20600	14000	0.325
Jinping Stage I	305	551.63	7760	3600	0.269
Longpan	276	551.23	37800	4200	0.408

SEISMIC ULTIMATE CAPACITY

Ultimate capacity of a structure against earthquakes can be defined as the strongest seismic load, under which the structure may suffer severe damage but can prevent sudden collapse. Retaining the stored water is the fundamental requirement for a dam, and it therefore should be able to prevent uncontrolled release of the reservoir during and after earthquakes. The assessment of ultimate capacity is often carried out by increasing the seismic load with certain increment to find out the minimum one which causes the failure of the structure, both numerical and physical model can be used for the assessment. As the seismic response of an arch dam is very complex, there could be several different failure modes. Then the assessment of its ultimate capacity requires appropriate simulation of the dam responses, appropriate determination of earthquake ground motion and proper interpretation of results (FERC, 1999, and FEMA, 2005) .

First, appropriate simulation of the dam responses under earthquakes is the basis to evaluate the ultimate capacity. The model used for the simulation, no matter numerical or physical, should include arch dam with the contraction joints, foundation rock near the dam with weak planes or discontinuities, if there are, and the reservoir, so that the dynamic interaction of the dam-foundation-reservoir system, radiation of dynamic energy to far field as well as the nonlinearity of material and contact can be taken into account properly. All static loads during routine operation and seismic load must be applied.

Second, the seismic effects are far more complicated than dead load effect. The earthquake ground motions are dependent on source characteristics, source-to-site transmission path properties, and site conditions. The motion varies along the dam-foundation interface due to limited wave speed in the foundation rock and seismic wave reflection and scattering. Commonly, it is assumed that the seismic motions incident vertically to ground surface from the deep rock according to the crustal structure and shear-wave velocity of the crustal rock. The design earthquake ground motions are defined on a free horizontal surface at a dam site, it is, however, hard to find so called free horizontal surface at mountainous dam site with canyon topography for the nominal design ground motion. The free horizontal surface is almost arbitrarily set in the model used for the simulation of seismic responses of an arch dam system, habitually near the elevation of the crest of an arch dam in order to limit the dimension of the model. Besides, the seismic responses are dependent on the dynamic properties of the structure. It is hard to use a single parameter to represent the level of earthquake ground motions. The response and the final damage of the structure may be sensitive to the peak ground acceleration, peak ground velocity, elastic response-spectrum, duration of time history and even the characteristics in phase spectra. That is why many researchers (Baker and Comell, 2004 and 2006, Bojórquez and Iervolino,2011, Buratti et al., 2011, Luco and Bazzurro,2007, Tothong and Luco,2007) carry out statistical analyses of a set of earthquake ground motions, in which an intensity measure such as PGA is scaled at the same level. In the assessment of the ultimate capacity of the arch dam, one set of time histories in three directions are commonly used and the level of the ground motions are increased by multiplying a factor over the whole time histories.

Finally, no concrete arch dam has been seriously damaged during past earthquakes and lost its function of retaining stored water yet, only a few damages are repairable and limited such as experienced by Pacoima Dam (County of Los Angeles, 1994). Possible failure modes of arch dams are not clear and closely related to the geological conditions of the dam site, especially in the abutment. The results of numerical or physical simulation can present several different modes. Cracking of the dam itself, sliding failure of the abutment rocks, sudden speeding up in deformation of the dam body, or even the divergent point are used to judge the failure in the numerical simulation.

SIMULATION BASED ON PHYSICAL MODEL TEST

Physical Model

The physical model of an arch dam system is generally a scaled one no matter for static or dynamic ultimate capacity test. It is unrealistic that a full scale arch dam model could be constructed for this kind of test. The main device for the dynamic test is the large shaking table, which can produce accurate simulation of earthquake ground motion as given. The whole model of an arch dam system will be mounted on the large shaking table.

To carry out dynamic ultimate capacity test, the dynamic dam-foundation interaction, dynamic dam-reservoir interaction, dynamic energy emission from near field to far field, opening and closing of contraction joints, sliding of abutment wedges, uplift pressure on the shear planes of the wedges and the overstressing of materials must been carefully simulated. Fig.1 shows the sketch of the physical model system of an arch dam used at China Institute of Water Resources and Hydropower Research (IWHR).

Besides the similarity in geometry, the scale physical model must meet the similarity in the material properties and that of all loads on the model of dam system. The geometry scale of a physical model is usually limited by the capacity and space of the platform of a shaking table. As 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. From the aforementioned three basic scales, all scales of other qualities, such as time, stress, etc. can be determined according to the theory of complete similitude, in which the strain scale, a dimensionless quality, is unity.

It should be noted that the geometry scale of a high arch dam for dynamic test may be as small as one hundredth or even smaller. And the scale in elastic modulus should be equal to the geometry scale according to the rule of similarity. Then the water in the model reservoir represents almost an incompressible liquid in the prototype reservoir. The water compressibility is therefore ignored in the physical model. Fortunately, the water compressibility has only small influence on the seismic responses of arch dams due to the sediment near the dam.

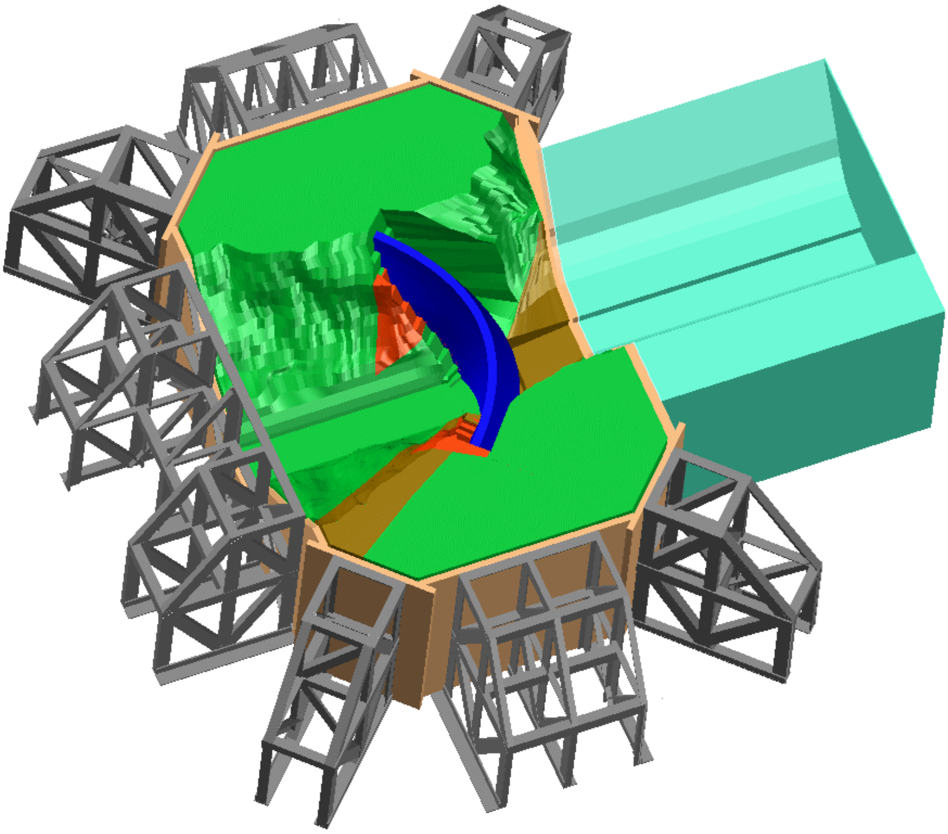

Figure 1. Sketch of an arch dam model on the shaking table

The Advantages and Difficulties in Physical Model Tests

Comparing with the simulation with numerical models, the preparation of a physical model of an arch dam system is a notoriously complex task. It is almost impossible to make modification when completed and the scale of the model is always restricted by the capacity of a shaking table. However, the advantage is that it is unnecessary to assume any algorithm for the contact or sliding, nonlinear strain-stress relations for the materials of dam and rock, the dynamic interaction of dam and water, as well as the iteration procedure in numerical simulation for the dynamic nonlinear problems. The results are direct and whether the damages threat the serviceability can be judged through visual observation. The results of the physical model test could be an important complement to the scarce experiences of high arch dams subjected to strong earthquake ground motion, will help to find the development of the damages, weakness of the arch dam sysytem and potential failure modes. Those are essential to study the ultimate capacity of arch dams against earthquakes.

Both results from the numerical simulation and physical test can be verified and complemented with each other, from which the engineer can reach a more comprehensive understanding and knowledge about the ultimate capacity of arch dams against earthquakes.

From the research works at IWHR, the main difficulties for the physical model test are the boundary condition, model material and model construction. The boundary conditions are closely related to the correct simulation of the radiation damping effect of the far field and the input of the ground motion.

Because the artificial boundary adopted in the simulation model will change the motion there anyway, taking larger foundation can theoretically decrease that influence on the seismic responses of an arch dam. However, including larger foundation will demand more computation effort in numerical simulation, or increase the total weight and the size of the model in the physical test for the same geometrical scale, that is restricted by the capacity of the shaking table. On the other hand, careful geologic investigation is concentrated near the dam, the rock properties as well as the structural geologic features and their shear strength parameters are in high degree of confidence. One has to assume the rock properties and major geologic features for the foundation beyond the geologic investigation area if the foundation range is simply extended in the simulation. That may not reflect correctly the influence of the real conditions on the dam responses. In the shaking table tests at IWHR, the foundation extension is about one time of model dam height in both upstream and downstream direction, a half to one time beyond left and right bank, and about a half times beneath the dam heel. Outside the foundation of the model, an artificial damping boundary layer consisted of viscous liquid is set in order to simulate the effect of dynamic energy emission from the near field to far field (Wang and Li, 2006 and 2007). Expected results were achieved in the view of the dissipation of vibrational energy, although further improvement should be made to simulate the radiation damping more precisely. The bottom of the model had to be connected to the shaking table with bolts, in consequence, the plane will move as the shaking table surface. For the corresponding plane in the prototype foundation, its motion varies due to scattering and reflecting of seismic waves by the complex topography of the dam site. The motion of the shaking table is an average one of the plane consisting of both incident wave from seismic source and transmitting wave from dam and foundation vibration.

It is not very difficult to find the model material which meets the similarity in both elastic modulus and density. But it is hard to find the low strength material as required by the scale and its preparation associates closely with the way of the model construction of an arch dam system. In the physical arch dam model, the strength scale is the same in value as the geometry scale, two-hundredth to three-hundredth for the dams of 200 to 300m in height. Therefore, the tensile strength of the model material should be as low as 0.01 to 0.015MPa if that of the dam concrete is about 3MPa. If the material is mixed with water and cased as the dam concrete, it is very hard to low its strength to meet the requirement and to avoid setting shrinkage. With naturally dried mixture of several kinds of powder, the material needs to be compressed on high pressure and the density, elastic modulus and strength are dependent on the pressure. It is then difficult to form the model dam directly from the mixture with high consolidating pressure. In practice, the model dam is constructed with bricks prepared, and the bricks are stuck to each other with bonding, except at the position where the contraction joints are to be simulated. Since the material is very weak, dam blank is first built and then carved to the shape of the dam requested. The strength cross the bond is usually higher than the brick itself, but to make two surfaces fully touched the shape tolerance of the bricks is very small.

Summary of the Recent Studies at IWHR

Many high arch dams have been carefully studied on the shaking table in recent years at IWHR. The major technical details of the dams are listed in Table 1. The shaking table is a six-degree-of-freedom digital-controlled servo-hydraulic system with a platform of 5m×5m. The maximum payload is 20,000 kg. The maximum accelerations, velocities, and displacements are 1.0 g, ±400 mm/s, ±40 mm in two horizontal directions, 0.7 g, ±300 mm/s and ±30 mm in vertical direction, respectively. Its working frequency band is 0.1 to 120 Hz.

Table 2. List of main test results

Dam Name	Maximum amplification of dam crest to dam heel	PGA of initial visible crack on dam (g)	Maximum acceleration responses of dam (g)	Maximum displacement of dam (mm)	PGA of initial permanent sliding of abutment (g)	Number of visible cracks on dam
Xiluodu	8.95	0.539	8.0	1203	0.80	8
Xiaowan	6.94	0.308	9.24	914.4	1.54	11
Xiaowan (functional joint)	10.98	0.616	11.9	1787.2	1.85	10
Dagangshan	7.9	0.557	7.0	291.3	----	10
Wudongde	4.81	0.769	5.6	1033.4	1.67	10
Baihetan	17.4	0.675	9.15	961.2	----	8
Jinping Stage I	9.15	0.975	7.2	1424.6	0.65	9
Longpan	6.0	(0.646)	3.99	235.6	0.54	1

In Table 2 are given the results of the physical tests. For Xiaowan arch dam, two physical models have been built. Since no perimetral joint near the dam heel at the time of the first model been built, the total tensile stress near dam heel was very high resulting in cracking there under the design level of earthquake ground motion. With the perimetral joint being simulated the acceleration level for initial cracking on the dam increased significantly for the second model. From these results, it is can be seen that the arch dams with long crest length show large amplification, about 9 times or even more, the maximum acceleration responses can be over 10g in the tests. One exception is the Wudongde arch dam with the shortest crest length, the amplification reached 17 times, and the maximum acceleration response was over 9g. This may be due to the high deformation modulus of the rock, the high fundamental resonant frequency of the dam and the topography near the dam heel and toe. The maximum displacement responses in the table are closely related to the crest length and the horizontal cracking of the model dams downstream. Because the complex geological condition, the highest arch dam, Jinping Stage I, displayed the lowest input acceleration for the initial irreversible sliding of the abutment wedges. However, the seismic responses of Jinping Stage I dam is much lower than other dams, its maximum acceleration response is only 4g. And the damage was very trivial after all dynamic overloading. The lowest sliding resistance of the abutment wedges and the smallest acceleration responses of the dam are correlative. It is common to use conservative sliding resistance parameters for abutment wedges in the design. But this may not lead to conservative results for the seismic responses of dam, since the sliding of the wedges will diminish the seismic motion transferred from the foundation rock to the dam. For the evaluation of the potential damages of the dam itself, therefore, higher sliding resistance parameters should be adopted in order to prevent overestimation of the dam itself.

For the above model tests, there is difference in the minimum ground motion for the initial cracking, initial permanent sliding of the wedges as well as the final visible damages on the dam. However, all the model dams remained stable under the static loads after the strongest input earthquake ground motion that the shaking table of IWHR can generate. At one accident that the shaking table was out of control and generated a strong sinusoidal motion lasting for tens of seconds cross the river, the abutment wedges of Xiaowan dam lost the stability completely so that the dam was seriously damaged near the abutments and in a state of unable to retaining water. Fig.2 is the photo of the dam seriously damaged from the downstream.

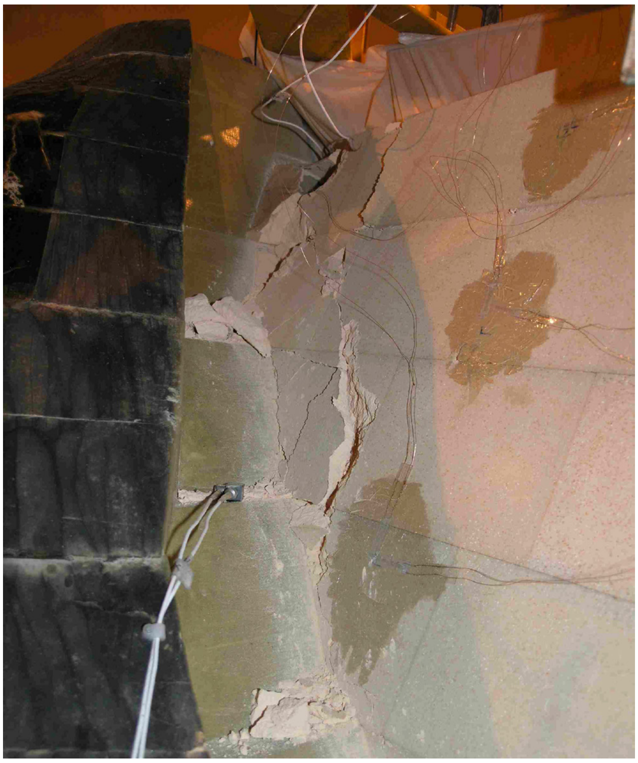

Figure 2. Photo of seriously damaged Xiaowan model dam by accident

From the results of physical model tests conducted at IWHR recently, three questions rise in mind. First, is it true that the seismic ultimate capacity of arch dams is far beyond our imagination? In both the real performances and physical model simulations of the arch dam systems, no serious damages have been observed that may threaten the serviceability of retaining water. Secondly, to find the seismic ultimate capacity of an arch dam system by physical model test, how strong the vibration should be generated by the shaking table? Whether the damages caused by sinusoidal excitation have any practical meanings to the study of the seismic ultimate capacity of an arch dam? Last one, what is the main difference of the dynamic damages of an arch dam system between the scale model and the full size model?

SIMULATION BASED ON NUMERICAL METHOD

In study of the seismic ultimate capacity of arch dam system at IWHR, an explicit finite element method in time domain is adopted to solve the propagation of seismic incident ground motions in the dam-reservoir-foundation system. The system consists of an interior region with the dam and its adjacent foundation rock and a far-field foundation region represented by energy transmitting boundaries. The contact or sliding of the contraction joints of the dam, dam-foundation interface as well as the shear planes in the abutment wedges were treated with a single-step method, in which, both the normal and shear contact forces can be considered, the contact condition and Mohr-Coulomb shear resistance can be satisfied in a single step without iteration. Besides, the width of any initial opening or initial tensile strength of the joints can be easy taken into account.

Under the strong earthquake excitations, local tensile overstress may cause cracking at upper portion of the arch dam and the dam-rock interface. However, if the local concrete cracks or the contraction joints open during the earthquake stress redistribution will take place in the arch dam as it is a redundant structure. On the other hand, these local damages as well as local sliding of abutment wedges will extent gradually as the intensity of the input seismic ground motion increases until the limit state of the integral stability of the arch dam system is reached. Because the integral stability of an arch dam is directly related to its serviceability of retaining the stored water in the reservoir, the inflexion on the relation between the displacement of the arch dam and the seismic input can be used to define its seismic ultimate capacity. If the loss of the integral stability is due to the sliding of the abutment wedges, their permanent displacements after earthquakes can be used for the assessment.

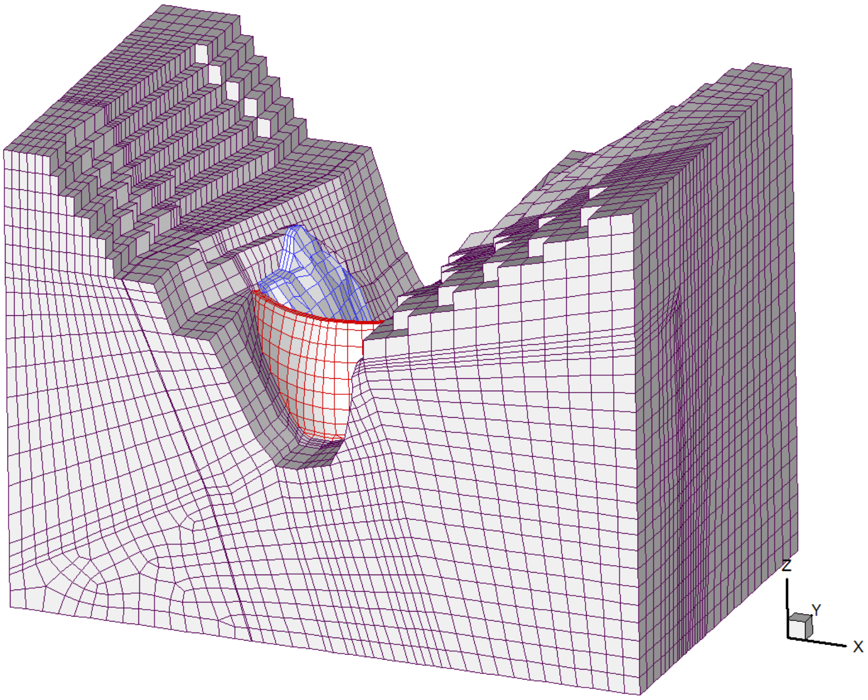

Figure 3. Mesh for numerical simulation of Jinping Stage I arch dam system

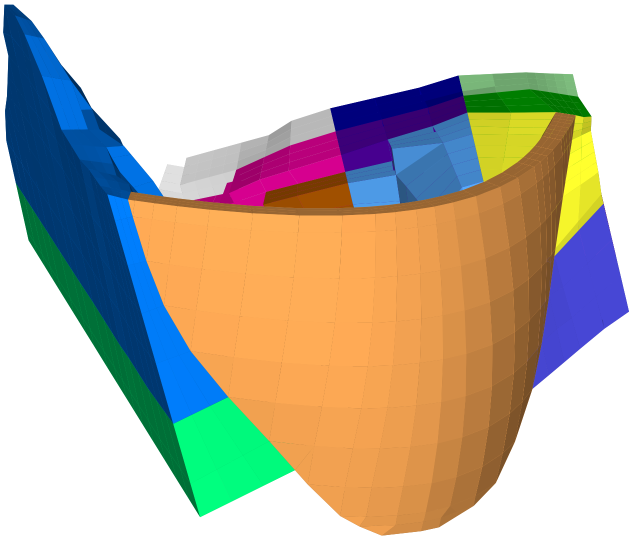

Figure 4. the dam and abutment wedges of Jinping Stage I arch dam system

As an example, Fig. 3 shows the mesh for numerical simulation of Jinping Stage I arch dam and Fig.4 shows the dam and abutment wedges. In Table 3 are listed the numerical results of the arch dams being investigated at IWHR recently. Actually, the arch dam systems do not loss its stability at once under the seismic input larger than the point of the inflexion in the table. The results would be more appropriately interpreted as the sign that the damages in the arch dam are in a more danger status and seismic responses become more difficult to be predicted. Comparing with the physical tests, these inflexion points are at the similar level of initial visible damages on the dams.

Table 3. List of main test results

Dam Name	PGA corresponding to the first inflexion (g)	Location of abrupt change in displacement	Number of wedges in the numerical model
Xiluodu	0.385	Dam-rock interface	2
Xiaowan	0.554	Left and right crest abutment	6
Dagangshan	0.697	Dam-rock interface	9
Wudongde	0.729	Right crest abutment	2
Baihetan	0.672	Right abutment wedge	7
Jinping Stage I	0.611	Abutment wedges	20
Longpan	0.694	Left crest abutment	2

The main difficulties in the numerical assessment of the ultimate capacity against earthquakes are properly modeling of the tensile cracking and crack propagation in the dam concrete and the foundation rock, as well as the sliding of the abutment wedges. As the damage of concrete and foundation rock is a result of continuous developing of random distributed micro cracks and small defects, traditional fracture theory developed for homogeneous material is not applicable. Cracking in the concrete and foundation rock is always accompanied with irreversible deformation but it is not fit with the classical plastic theory based on the crystal dislocation, especially for the tensile loading. Many new damage theories with damage variable and smeared crack model for the damage rupture of concrete dams have been proposed in recent years (Gopalaratnam and Shah,1985, Chen et al., 2013). They are still required to be calibrated with more experimental data of the dam concrete. Besides, the problem of instabilities in numerical schemes always goes along with the nonlinear analyses. The larger the portion of the structures deteriorated due to cracking, the harder the numerical process to reach convergent results. And the results are dependent on the experience and skill of the experts.

CONCLUSIONS

The seismic ultimate capacity of the high arch dam system in seismic region is a major challenge to the scientific community and has been receiving a lot of attention lately in China. The society as well as the designers concerns deeply the safety of these high arch dams if strong earthquakes occur close to them. Both numerical simulations and physical tests have been carried out at IWHR to study the process of cracking and the mechanism of damage of the dams. In the physical models for dynamic tests, a very low strength model material was developed, its tensile strength, density and stiffness characteristics match the similitude requirements. The contraction joints of the dam, abutment wedges and radiation damping at the artificial boundary were simulated. Special air jacks were introduced to simulate the effect of uplift pressure on the sliding surfaces. All the model dams remain stable under the static loads after the strongest input earthquake ground motion that the shaking table of IWHR can generate, although there were many visible cracks on the model dams. In the numerical simulations of dynamic nonlinear seismic responses, the inflexion on the relation between the displacement of the arch dam and the seismic input has been used to define its seismic ultimate capacity, which should be regarded as the smallest value reasonablely. If the loss of the integral stability is due to the sliding of the abutment wedges, their permanent displacements after earthquakes can be used for the assessment.

All the results presented in the paper are only a beginning, more innovative researches and detailed efforts are required to improve both the numerical and physical simulations to make our knowledge about the seismic ultimate capacity of the arch dam more complete and more comprehensive.

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