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Potential Failure Mode of Arch dam Revealed by Shaking Table Tests

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Abstract

Dam safety during strong earthquakes 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 past earthquakes. However, it should be noted that seldom dams are located very close to the faults of 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, 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.

The uncertainty of earthquake ground motions is so large that the real earthquake ground motions may exceed the design level despite of very low probability of such 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 that limits our imagination about the potential failure mode of arch dam under destructive earthquakes. Then the shaking table test of arch dam with scaled model can play a supplementary role to discover the potential failure mode.

Recent shaking table tests presents interesting results of an arch dam under strong earthquakes. In the scaled model for shaking table tests, a very low strength model concrete was developed, its tensile strength, density and stiffness characteristics match the similitude requirements. The contraction joints of the dam, the upstream reservoir, abutment wedges, the effect of uplift pressure, as well as radiation damping at the artificial boundary were simulated. As the intensity of the shaking increased, horizontal cracks near the upper part of the arch dam were observed first, followed with strong impact as the cracks and the contraction joints opening and closing during the shaking. When the impact was strong enough, crash of the concrete happened and destabilized the concrete blocks detached significantly, which would finally lead to the uncontrollable release of reservoir as the detached blocks may fall down from either upstream or downstream direction. Even if no falling down happens, the leakage of the dam body makes it lose the function to retain the water in the reservoir.

Keywords: arch dam, shaking table test, failure mode, crack, compressive damage

1. 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 was 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 a dam resulting in an uncontrolled release of the reservoir.

Dam safety during strong earthquakes 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 earthquakes [1 to 4]. 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, but only 8 arch dams have experienced ground motion over or close to their design levels. They are Pacoima dam [5], Lower Crystal Springs dam and Gibraltar dam in the United States, Ambiesta dam in Italy, Shapai dam [4] and Techi dam in China, Rapel Dam in Chile and Shin Toyone dam in Japan.

It is very difficult to predict precisely earthquake ground motions for a structure in its life-cycle period [6 to 8]. 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 dam 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 [9]. 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 [10].

Both numerical simulation and physical model test of arch dam systems have been conducted in recent two decades at China Institute of Water Resources and Hydropower Research (IWHR) to study the seismic responses as well as the seismic ultimate capacity [11 to 14]. In this paper, we will explore the potential failure mode of arch dams based on the shaking table tests.

2. Arrangement of shaking table model tests

The physical model of an arch dam system is generally a scaled one, no matter for static or dynamic test. It is unrealistic that a full scale arch dam model could be constructed for this kind of test. The main equipment for the dynamic test is a large shaking table, which can produce accurate simulation of earthquake ground motion as defined. The whole model of an arch dam system will be mounted on the 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 a sketch of the physical model system of an arch dam constructed at China Institute of Water Resources and Hydropower Research (IWHR). Fig.2 presents the sliding surfaces of the abutment wedges and 7 contraction joints that were simulated in the test model.

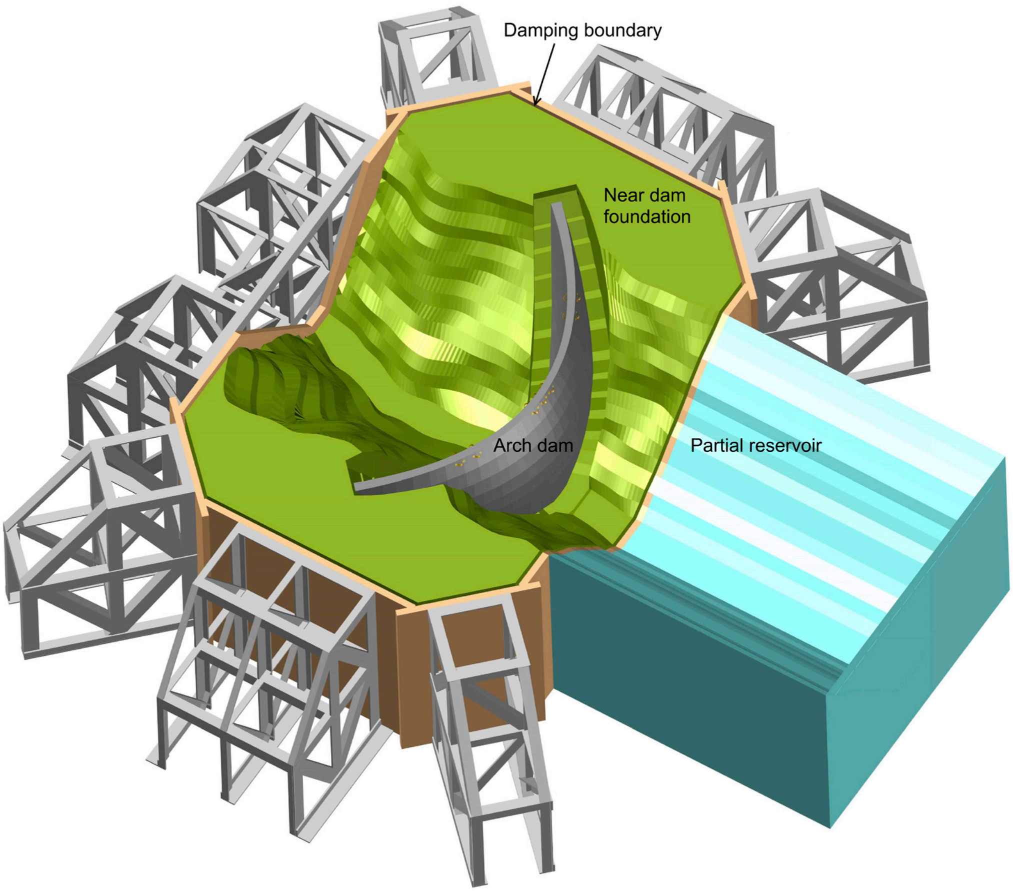

Fig.1 – Sketch of an arch dam model on the shaking table

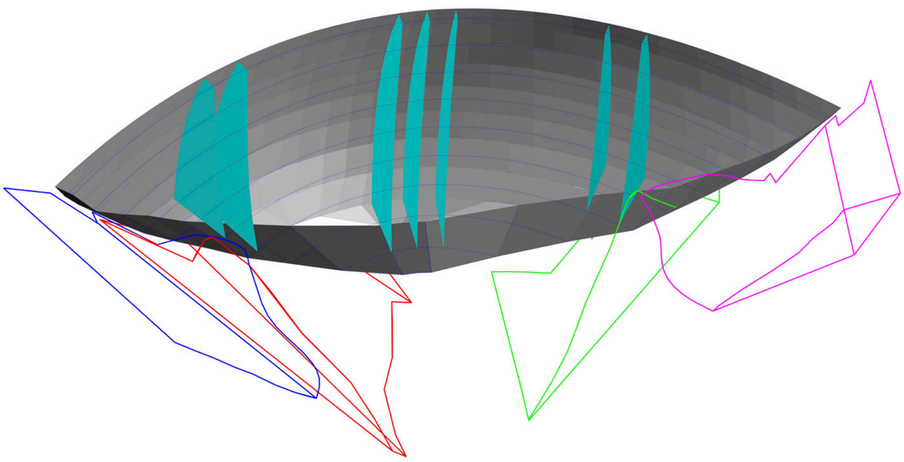

Fig. 2 – Sketch of the abutment sliding surfaces and contraction joints simulated

Besides the similarity in geometry, the scale physical model must meet the similarity in the material properties and all the loads on a dam system. The geometrical scale of a physical model is usually limited by the capacity of the payload and the space of platform of a shaking table. As water is the only rational selection of the liquid in the model reservoir to simulate the dam-water interaction, it is required that the density scale of material and the scale of acceleration must be unity so that the hydrostatic pressure in a normal gravitational field can be correctly represented. From 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 geometrical 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 geometrical scale according to the requirement of similarity. Then the water in the model reservoir represents almost an incompressible liquid in the prototype reservoir. In consequence, the water compressibility is ignored in the physical model. Fortunately, the water compressibility has only small influence on the seismic responses of arch dams due to the sediment in the reservoir near the dam.

3. Test Program

The seismic motions were input in three directions simultaneously for our dynamic tests. Started with the ground motion of design level, which can be different for every project in both wave form and PGA, the exicitation intensity was increased by multiplying a factor over entire time histories for seismic overloading. As a result, the wave forms could be kept unchanged for all levels. Fig.3 gives an example of the response spectra of the acceleration on the surface of the shaking table for seismic overloading from 1.5 to 6.0 times of the design level, the period in the figure is the scaled model time. It is easy to confirm from the figure that the wave forms are almost the same. This made it easy to compare the responses between different levels of seismic overloading. The responses of the model under the white noise excitaion of 0.05g were measured both before and after every seismic input in order to identify the dynamic characteristics of the model dam, as any change in the natural frequencies of the arch dam system reflects some structural variation or damage. It is should be mentioned that, as the same model dam was shaked many times, the damage of the dam system will accumulate for every loading.

Besides the data acquisition of more than 180 channels instrumented on the model dam system, usually with a sampling frequency of 2000Hz, high speed camera of 1000 frames per second was used as well to catch the open of contraction joints as well as the crack and further damage on dam body.

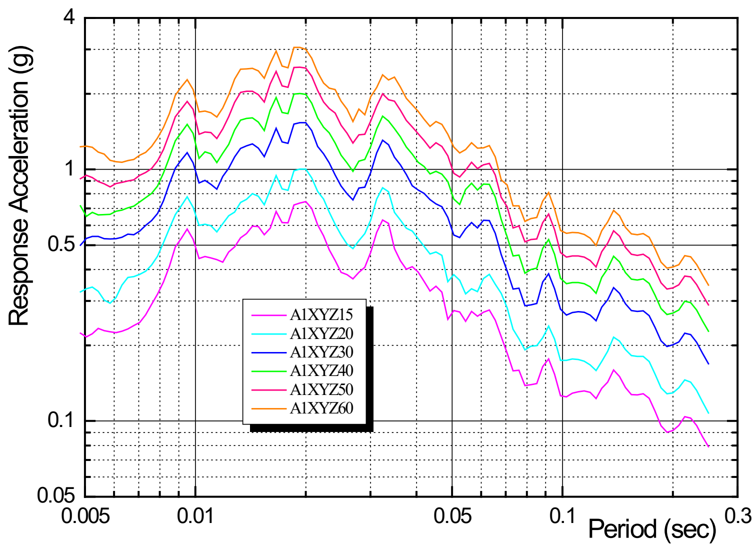

Fig. 3 – Response spectra of the acceleration on the table surface for seismic overloading

4. Responses of Acceleration and displacement

In Table 1 are given the results of 10 arch dam model tests. For Xiaowan arch dam of 292m in height, two physical models have been built. Since no perimetral joint near the dam heel at the time that the first model was built, the total tensile stress near dam heel was very high resulting in cracking there at 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 amplification of arch dam is large, from 6 to 11 times in acceleration, except only one dam. This amplification is simply the ratio of the acceleration on the crest to that at the toe of the crown. The maximum acceleration responses can be over 10g on the crest of the dams in the tests, and the average was about 7.5g. Wudongde arch dam of 265m in height in a narrow valley presented an amplification of 17 times, much higher than all other dams, the maximum acceleration response was over 9g. This exceptional case may be due to the high deformation modulus of the rock, close to the dam concrete, the high fundamental resonant frequency of the dam and the topography near the dam heel and toe. The maximum displacement responses shown in the Table 1 are closely related to the crest length as well as the horizontal cracking of the model dams downstream, the average value was about 879mm. Because the complex geological condition, the abutment wedges of the highest arch dam, Jinping Stage I of 305m in height, was found to undergo initial irreversible sliding at the lowest input acceleration. On the other hand, the seismic responses of Jinping Stage I arch dam is much lower than others. Its maximum acceleration response was only 4g. And the damage was very trivial after all dynamic overloading, up to the maximum capacity of the shaking table at IWHR. It can be judged that 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 of arch dams for static loads. But this may not lead to conservative results for the seismic responses of dams, since the sliding of the wedges will diminish the seismic motion transferring from the foundation rock to the dam. Much caution is necessary 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.

Table 1 – List of the responses of arch dams

Dam Name	Maximum amplification of acceleration	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	8.00	1203.0	0.80	8
Xiaowan	6.94	0.308	9.24	914.4	1.54	11
Xiaowan (perimetral joint)	10.98	0.616	11.9	1787.2	1.85	10
Dagangshan	7.90	0.557	7.00	291.3	----	10
Wudongde	17.4	0.675	9.15	961.2	----	8
Baihetan	9.15	0.975	7.20	1424.6	0.65	9
Jinping Stage I	6.00	(0.646)	3.99	235.6	0.54	1
Longpan	6.17	0.572	6.57	650.8	0.49	8
Mengdigou	7.20	0.666	6.50	944.0	0.67	12
Yebatan	8.60	0.531	5.40	336.2	1.06	12
No.10	8.80	0.845	7.37	920.1	1.27	20

5. Dynamic damages

For the above arch dam model tests, there is difference in the minimum ground motion PGA for the initial visible cracking on dams, ranging from 0.53 to 0.97g and the average value was about 0.66g, except for the first model of Xiaowan without perimetral joint. The minimum ground motion PGA for the initial permanent sliding of the wedges of each model dam ranged from 0.49 to 1.85g.

Because of the opening of the contraction joints of arch dam during the shaking of earthquakes, the function of arch vanished when the dam monolith moved upstream and horizontal cracking occurred in cantilever direction first for most of model dams as the seismic input increased. Some cracks can also be observed near the abutment, shown in Fig. 4 for Yebatan arch dam as a typical example. After the strongest input earthquake ground motion that the shaking table of IWHR can generate, the dynamic damages of most model arch dams limited to the cracks due to the tension, but for Wudongde, Mengdigou and No.10 arch dams compressive crush or compression shear failure of dam concrete have been observed. The most seriously damaged one was No.10 arch dam listed in Table 1. This kind of compressive damage may result in a final failure of arch dam directly.

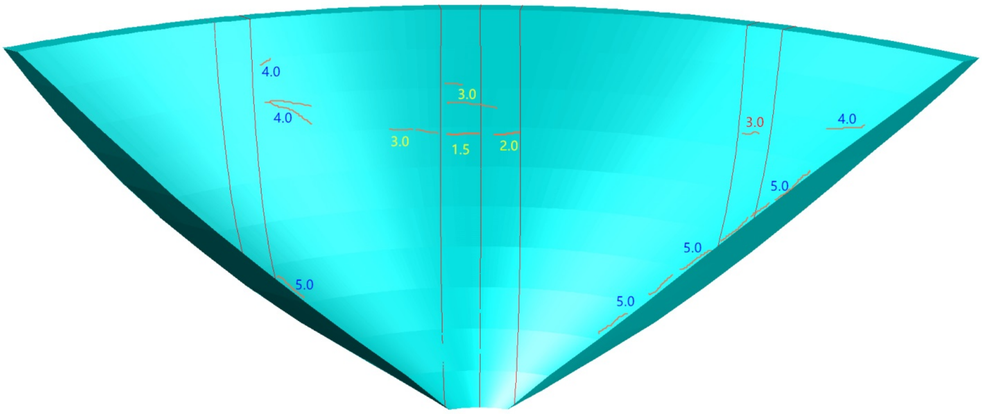

Fig. 4 – Cracks on Yebatan arch dam (the numbers are the times of overloading)

Fig. 5 – The photo of No.10 arch dam before test

For details of the damages, Fig.5 is the photo of No. 10 arch dam before testing, its height is 167.5m, Fig.6 gives the photo of the dam after testing with many damages, and Fig.7 presents the enlargement of the final damage marked with a circle on Fig.6. Evident compressive damages were observed in Fig.7 that crushed the dam concrete. Fig. 8 is the snapshot of cracks, captured by high speed camera, before compressive damage on No.10 arch dam during shaking, the elevation of the cracks on each monolith was different a little. The compressive damage was not limited to the cracking part of the dam only, at contraction joints, strong compacting along with the joints closing made considerable amount of dam concrete fell apart, as compression shear failure, as shown in Fig.9 for No.10 arch dam and Fig.10 for Wudongde and Mengdigou arch dams. Accompany with the further development of compressive damages on the dam body during strong earthquakes, the possibility of the loss of stability of the upper part of dam will increase significantly, that could finally result an arch dam failure mode neither being experienced in real dams nor predicted with numerical analysis during earthquakes yet.

For No.10 arch dam, although no detached concrete block fell down during the test, the damages on dam body (Fig.6, Fig.7 and Fig.11) indicated that the function of retaining water was destroyed greatly and no engineer or administer will allow the real dam to operate normally anymore without repairing or even partially rebuilt.

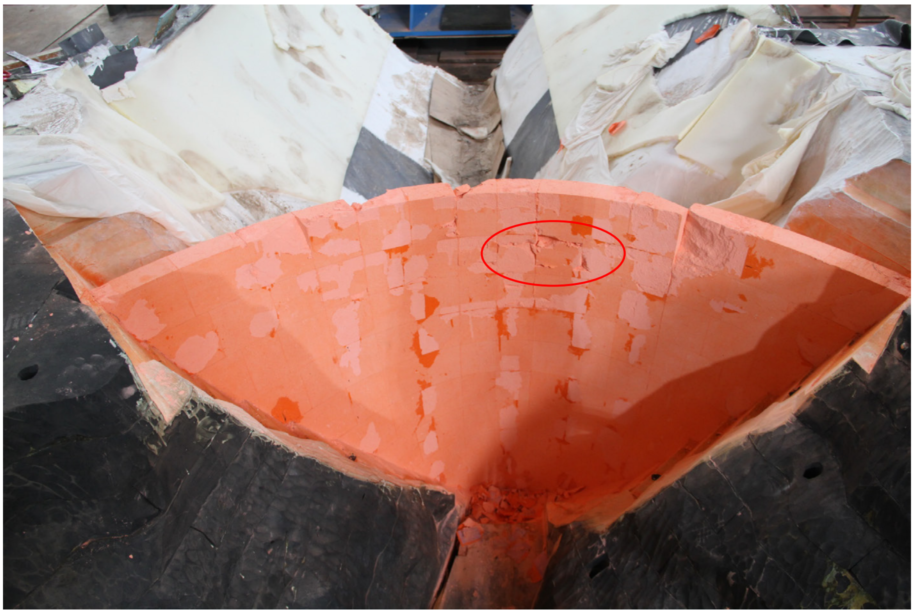

Fig. 6 –The photo of No.10 arch dam after test

Fig. 7 – Enlargement of the final damage of No.10 arch dam

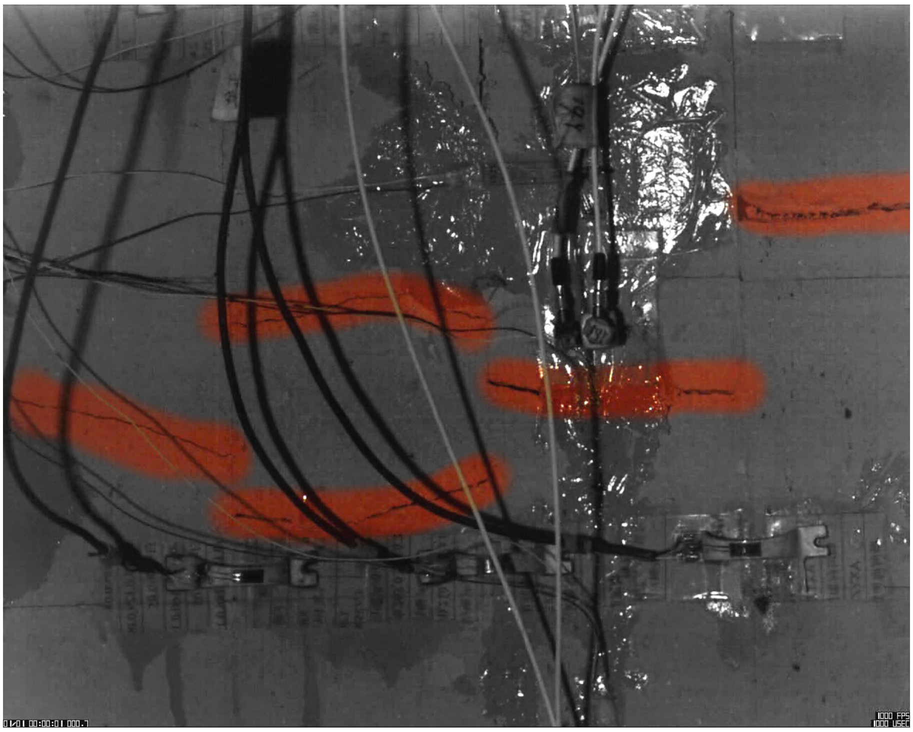

Fig. 8 – The snapshot of cracks on No.10 arch dam during dynamic loading

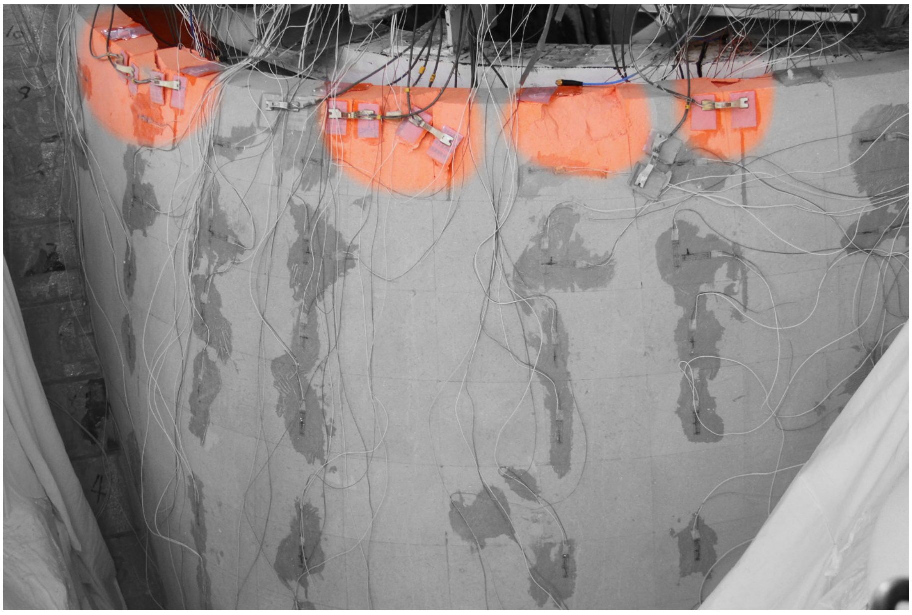

Fig. 9 – Compressive damages at contraction joints of No.10 arch dam

6. Conclusions

Failure mode of an arch dam is important when we need to predict its ultimate capacity under earthquakes. However, due to the lack of real failure data related to existed arch dams, dynamic physical model tests become a complementary way to study the possible failure mode of arch dams, despite of some difference between prototype and scaled model dams.

Many shaking table tests on arch dam have been conducted at China Institute of Water Resources and Hydropower Research (IWHR) in recent two decades. In our dynamic tests, the dynamic dam-foundation interaction, dynamic dam-reservoir interaction, dynamic energy emission from near field to far field, the contraction joints, abutment wedges, uplift pressure on the shear planes of the wedges and the overstressing of materials have been carefully simulated.

These dynamic tests reveal that the minimum ground motion PGA for the initial visible cracking on dams, ranging from 0.53 to 0.97g and the average value was about 0.66g, and the amplification of arch dam is large, ranges from 6 to 11 times in acceleration, the maximum acceleration responses can be over 10g on the crest in our tests, and the average value was about 7.5g, the maximum displacement responses are closely related to the crest length as well as the horizontal cracking downstream on the model dam, the average value was about 879mm, the minimum ground motion PGA for the initial permanent sliding of the wedges of each model dam ranged from 0.49 to 1.85g.

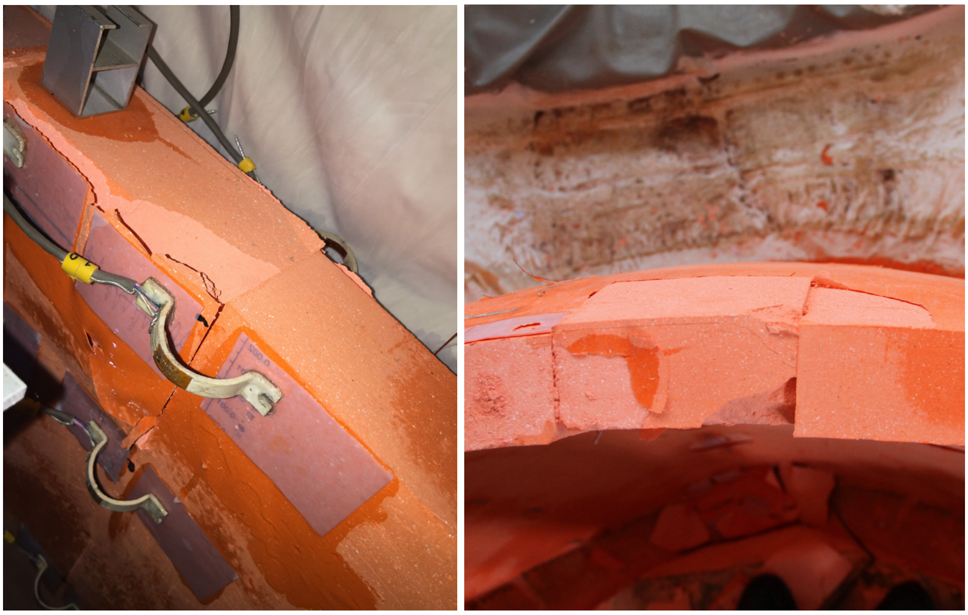

Fig. 10 –Compression shear failure at the joints of Wudongde(left) & Mengdigou(right) dam

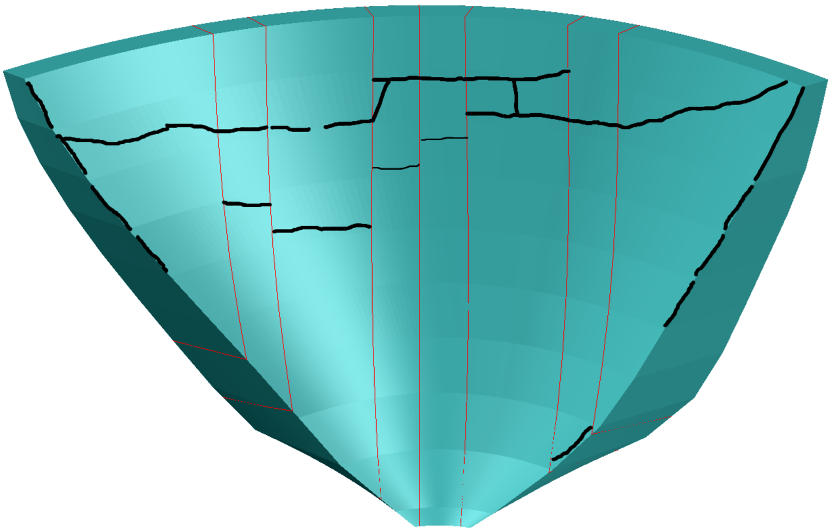

Fig. 11 –Damages on No.10 arch dam (downstream view)

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Accompany with the further development of compressive damages on the dam body during strong earthquakes, the possibility of the loss of stability of the upper part of dam will increase significantly, that could finally result an arch dam failure mode neither being experienced in real dams nor predicted with numerical analysis during earthquakes yet.

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