The Performance of High Dams in Wenchuan 5-12 Earthquake and Follow-up Analysis of the Shapai Arch Dam during the Event

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SUMMARY:
We briefly introduce the seismic performance and damage of four high dams (>100 m high) during the Wenchuan 5-12 earthquake, and further analyze earthquake response of the Shapai Roller Compacted Concrete (RCC) Arch Dam using 3D finite element modelling, and explain the mechanisms of its excellent performance during the event. Finally, concluding remarks on aseismic design of high dams in China are discussed.

Keywords: Wenchuan 5-12 earthquake, high dams, follow-up analysis, aseismic design

1. GENERAL REVIEW OF HIGH DAM PERFORMANCE IN WENCHUAN EARTHQUAKE

Wenchuan Earthquake with a magnitude of 8.0 and focal depth of 15 km, occurred on May 12, 2008 in the Longmenshan fault belt, western Sichuan. Regarding hydro-structure performance, totally 1,800 dams, 470 hydropower plants with installed capacity of 3.3 GW, and other hydro-structures were affected. Among them, more than 800 dams and sluices of different types experienced different extent of damage, although not one collapsed. Among these, the Zipingpu Concrete Face Rockfill (CFR) Dam, the Shapai Rolled Compacted Concrete (RCC) Arch Dam, the Bikou Earth-Rockfill Dam, and the Baozhusi Gravity Dam are the key hydro-projects. All four dams are located in the zones of earthquake-affected intensity of VIII-X but with only slight damage except Zipingpu Dam. Herein, for understanding their seismic performance, we used finite element scheme to analyze the dynamic response of the Shapai RCC Arch Dam, and remarked on aseismic design of high dams in China. The 33 affected dams which have installed power capacity >30 MW in the region with the earthquake affected intensity >VII are shown in Figure 1.1. The four key projects with dam height >100 m are listed in Table 1.1 and their performance during the event can be summarized in the following (Zhang C.H. 2011, Wieland M. & Chen H.Q. 2010, Yan Z.Y. *et al.* 2009).

Table 1.1. Characteristic features of four high dams during the Wenchuan 5-12 earthquake

Name of project	Number in Figure 1.1	Dam type	Dam height (m)	River	Distance to epicenter (km)	Distance to rupture surface (km)	Wenchuan affected intensity	Design PGA (g)	Damage category*
Zipingpu	9	CFR	156	Minjiang R.	17	8	IX~X	0.26	3
Bikou	31	Earth-Rockfill	101.8	Bailongjiang R.	261(24)	73(17)	IX	0.2	2
Shapai	17	RCC Arch	132	Minjiang branch	36	32	VIII	0.138	4(power house) 1(dam)
Baozhusi	32	Gravity	132	Bailongjiang R.	268(21)	80(9)	VIII	0.15	2

* Damage category is defined as following: 1-intact; 2-light damage, can be repaired shortly; 3-relatively serious damage, repairable within one year; 4-serious damage, need 2~3 years to repair; 5-complete failure, not repairable.

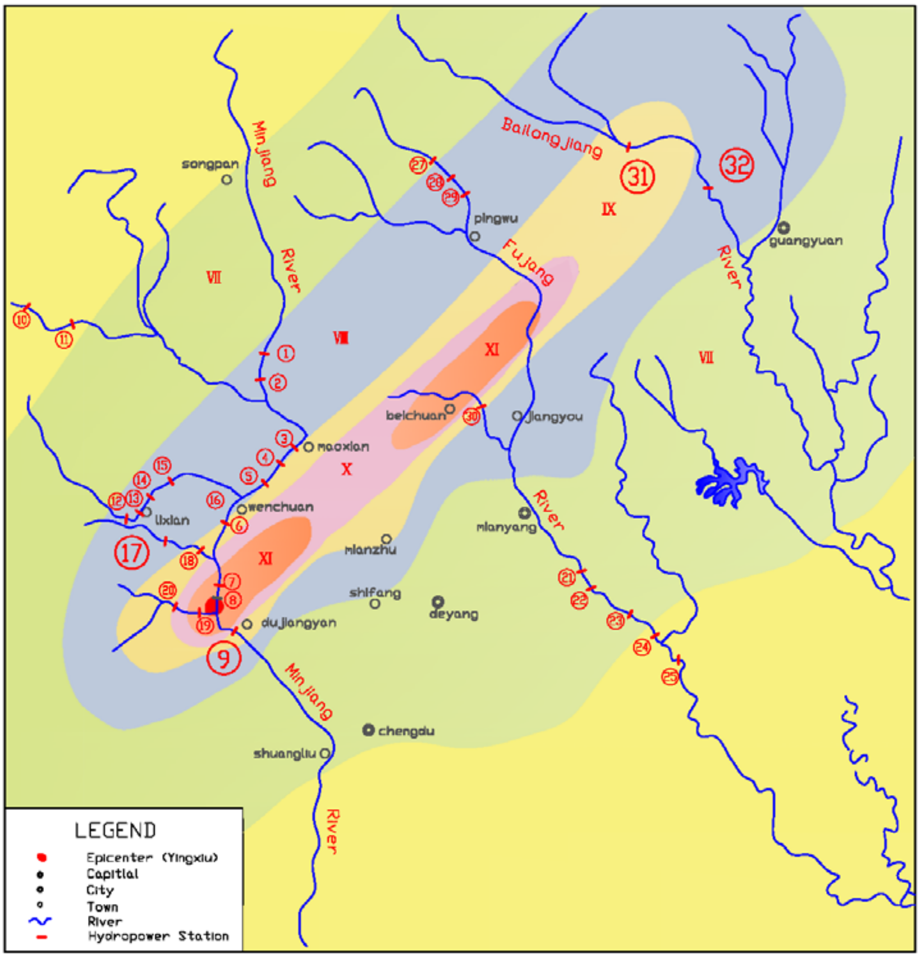


Figure 1.1. Intensity contour of the Wenchuan 5-12 earthquake and the location of the affected dams

1.1. Zipingpu Concrete Faced Rockfill (CFR) Dam

The 156 m-high Zipingpu Dam is located 17 km away from the epicenter of the earthquake. The peak ground acceleration (PGA) was estimated around 0.65 g-0.8 g, far beyond the design PGA of 0.26 g. The dam was subjected to very strong shaking in the earthquake, with the affected intensity of IX-X degree. The reservoir level was only 100.74 m in depth during the event. The damage of the dam can be summarized as following (Figure 1.2): (1) the maximum settlement at crest reached 810 mm and horizontal deflection reached 180 mm toward downstream; (2) seepage quantity increased from 10 L/s to 20 L/s; (3) vertical and horizontal slippage of the joint were 350 mm and 170 mm respectively; (4) serious collapse of the sidewalk guardrail and other auxiliary facilities at the crest; and (5) significant uplift and loosening of the downstream protection stone. Detailed discussion of the damage may be referred to Zhang C.H. (2011).

1.2. Shapai Roller Compacted Concrete (RCC) Arch Dam

The 132 m-high Shapai Dam is 36 km away from the epicenter. When the earthquake occurred, the reservoir was full, with a normal water level of 128 m in depth. The design PGA of Shapai Dam is 0.138 g, but the affected intensity reached VIII-IX degree. However, the dam was intact with no crack observed after the reservoir was emptied (Figure 1.3(a)). The abutments also remained stable. The dam foundation did not show significant difference of the seepage. The only severe damage was that the penstock was destroyed by falling stones, resulting in serious flooding of the power plant (Figure 1.3(b)).

(a) Concrete face joint breakage and slip (b) Collapse of fence columns at crest

Figure 1.2. The performance and damage of the Zipingpu CFR Dam

(a) No cracks observed in the dam after reservoir emptying (b) Penstock breakage and power plant flooded

Figure 1.3. The performance and damage of the Shapai RCC Dam

1.3. Bikou Earth-Rockfill Dam

The damage of the 101.8 m-high Bikou Dam includes: (1) collapse of downstream wall at the crest (Figure 1.4(a)); (2) the extrusion and opening of the contraction joints of the upstream protection wall (Figure 1.4(b)); and (3) the maximum crest settlement reached 242 mm and maximum horizontal deflection reached 154 mm toward upstream.

(a) Downstream wall collapse at crest (b) Wave protection wall contraction joint opening and crush

Figure 1.4. The performance and damage of the Bikou Earth-Rockfill Dam

1.2. Baozhusi Gravity Dam

The 132 m-high Baozhusi Dam is 260 km away from the epicenter. The dam was at a low water level of 71.5 m in depth when the earthquake occurred. The damage details include: (1) an increase in seepage quantity from 35.6 to 59.1 m^3/h, (2) opening, cracking and extrusion of the contraction joints (Figure 1.5(a)); (3) cracking of the guardrail; and (4) the 33t hoisting device at the crest had a permanent residual movement of 430 mm toward the left abutment and 50 mm toward downstream (Figure 1.5(b)).

(a) Joint opening and cracking at crest (b) Movement of the hoisting equipment along dam axis

Figure 1.5. The performance and damage of the Baozhusi Gravity Dam

2. FOLLOW-UP ANALYSES OF THE SHAPAI RCC ARCH DAM

The finite element discretization for the dam and foundation is shown in Figure 2.1. Both linear and nonlinear analyses with the latter considering contraction joint opening are accomplished. The input motions are either produced from the spectrum of the State Design Specification (DL 5073-2000) or the field measurements recorded during the Wenchuan main shock at the LixianTaoping station that is 28 km away from the dam site. The response spectra of the input are shown in Fig 2.2. Evidently, the field records have narrower band of predominant frequencies but higher amplitude of peaks compared with the design specification spectrum. The ratios of stream/ cross-stream/ vertical components are 1/ 1/ 0.67. The maximum peak accelerations are assumed to be 0.2 g, 0.3 g and 0.4 g that are equivalent to the estimated affected intensity of VIII-IX. The hydrodynamic pressure of reservoir water is considered with Westergaard additional mass model. The following cases of analysis are performed.

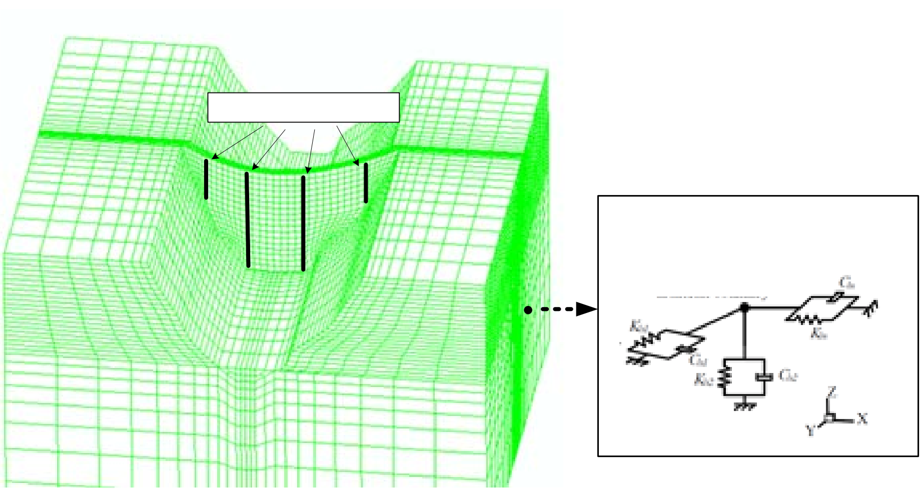


Figure 2.1. Finite Element model of the Shapai dam and foundation

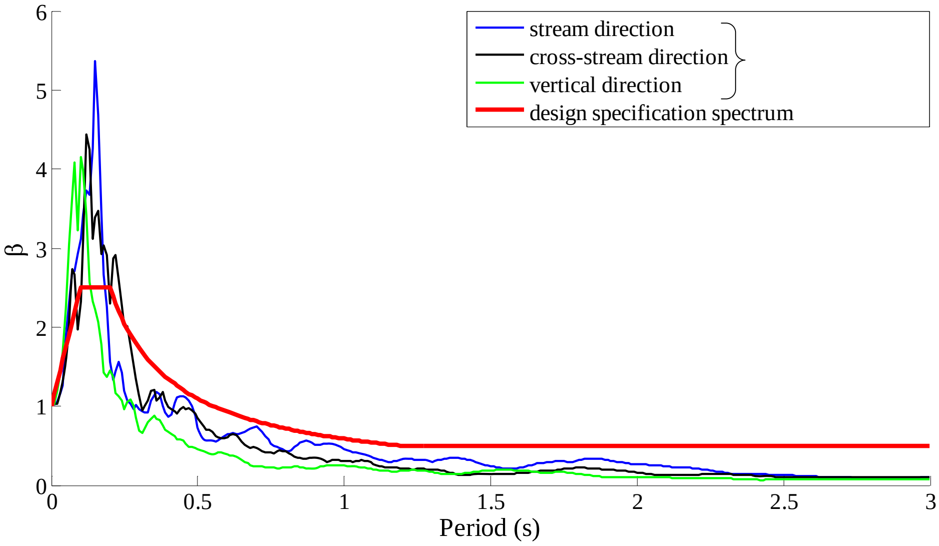


Figure 2.2. Response spectra of the input motions

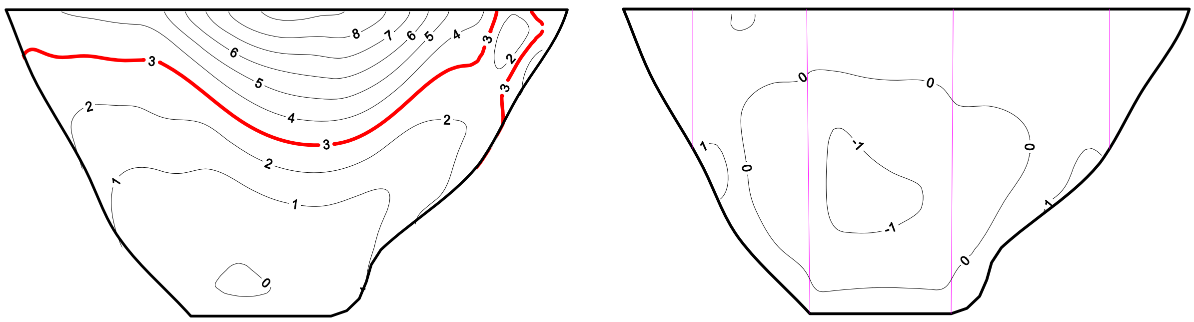
2.1. Linear Analysis and Massless Foundation

The foundation rock is assumed to be massless (Cough R.W. & Penzien J. 1993). For the input motion, both time histories from design spectrum and field records are used for comparison. The results are listed in Table 2.1 and Figure 2.3(a).

Table 2.1. Maximum tensile stresses (MPa) of the dam with inputs of the design spectrum and field records

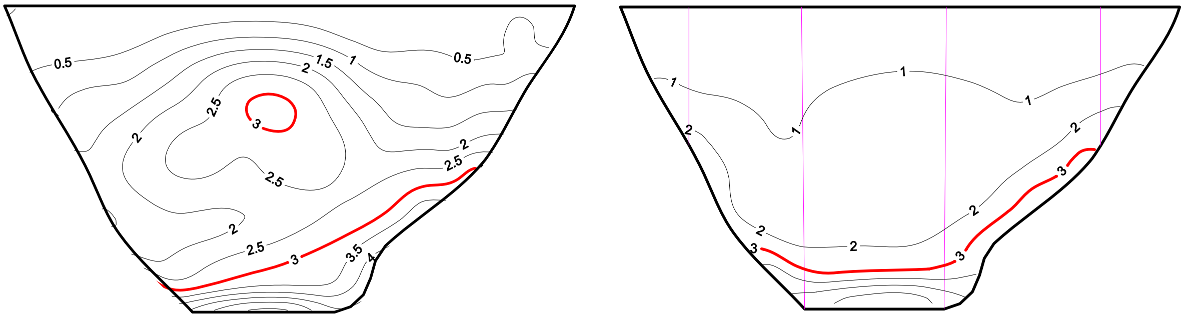
PGA	Upstream dam surface				Downstream dam surface			
	Arch stress		Cantilever stress		Arch stress		Cantilever stress	
	Field records	Design spectrum	Field records	Design spectrum	Field records	Design spectrum	Field records	Design spectrum
0.2 g	2.84	4.08	1.44	1.45	3.06	3.53	1.58	1.67
0.3 g	4.95	6.77	2.80	2.27	4.95	5.63	2.41	2.51
0.4 g	7.05	9.41	4.16	3.20	6.80	7.70	3.24	3.37

From the results, it may be concluded that, with excitation of both the design spectrum and field records, the dam body shows large maximum tensile stresses, and their maximum values reach 3 MPa and 4 MPa respectively under the input motion of 0.2 g. The maximum tensile stresses may even reach 7 MPa and 9 MPa in the case of 0.4 g as the input, which far exceed the tensile strength of concrete.



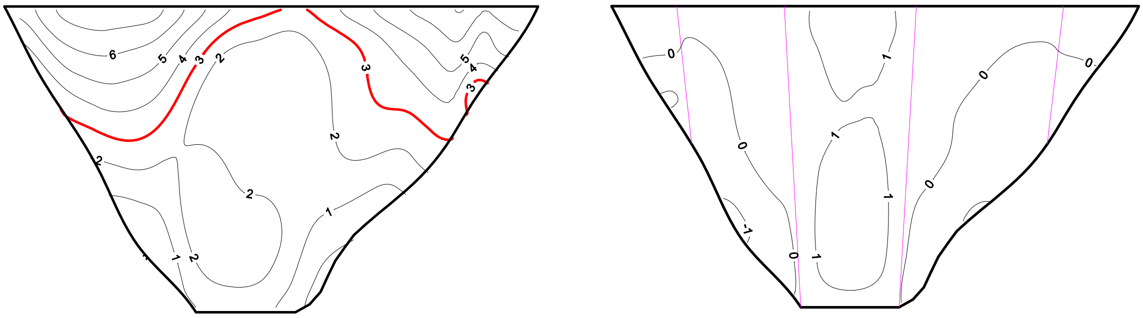
(a) (b)

(I) Tensile arch stress on the upstream dam surface



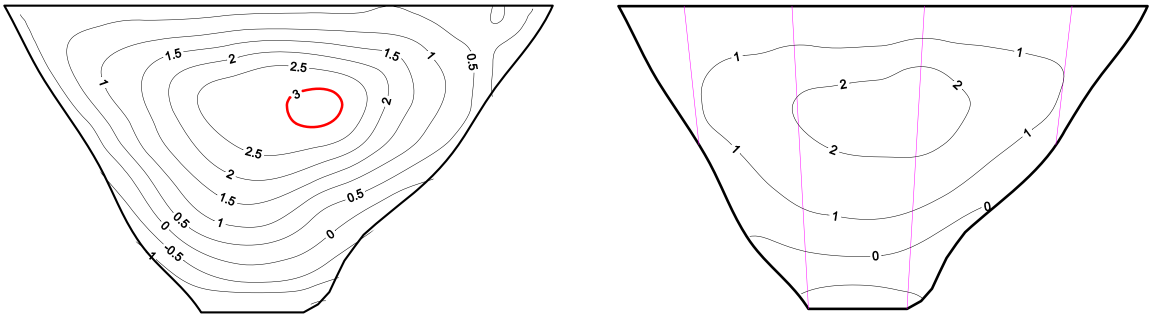
(a) (b)

(II) Tensile cantilever stress on the upstream dam surface



(a) (b)

(III) Tensile arch stress on the downstream dam surface



(a) (b)

(IV) Tensile cantilever stress on the downstream dam surface

Figure 2.3. Contours of the maximum tensile stress (MPa) on the dam surface under the field records of 0.4 g (a) Linear, massless foundation; (b) Joint opening, viscous-spring boundary

Also, the maximum stress contours (Figure 2.3(a)) especially in arch direction show the tensile stresses in a large area of the dam surface exceed 3.0 MPa, the prescribed tensile strength for the designed concrete of the dam. If the linear model and the assumption of the massless foundation were applied, the dam would have suffered in severe cracking. However, the real performance of the dam was entirely intact without occurrence of damage. The results indicate the current procedures of linear assumption and massless foundation are conservative and overestimate the dynamic response in safety evaluation of arch dams. Therefore, nonlinear analysis with contraction joint opening and radiation damping of infinite canyon is further performed for understanding the prototype behaviour of the dam during the earthquake.

2.2. Nonlinear Analysis with Joint Opening and Radiation Damping of Infinite Canyon

Since the linear analyses with either design specification spectrum or field records provide similar results of maximum tensile stresses (Table 2.1), herein, only the design specification spectrum is used as the input for the nonlinear analysis. For consideration of radiation damping effect, the viscous-spring boundary input model is applied. Three pairs of dashpots and springs are installed in each node of artificial boundary as shown in Figure 2.1. The determination of spring and dashpot parameters and the input procedure can be referred to Zhang C.H. *et al.* (2008). For modelling the contraction joint opening, the contact boundary model with tangential spring is used (Bathe and Chaudhary 1985). Four contraction joints simulated in the model are shown in Figure 2.1. The results of maximum tensile stresses in the case of 0.4 g as the input PGA are shown in Figure 2.3(b). The following remarks may be drawn:

(i) With consideration of nonlinear behaviour due to contraction joint opening and radiation damping due to infinite canyon, the maximum tensile stresses are dramatically reduced. Even in the case of 0.4 g as the input motion, the maximum tensile stresses are lower than the designed tensile strength of concrete, i.e. 3 MPa except the cantilever stress of upstream heel due to effect of stress concentration. The results strongly support the real performance of the Shapai dam that was entirely intact during the event.

(ii) By examining the stress distribution shown in Figure 2.3, the arch stresses on both upstream and downstream faces are almost completely released due to the two factors of joint opening and radiation damping. However, the stresses at upstream cantilever heel and downstream upper body remain a level of 2-3 MPa due to the counteract effects of the two factors on the dynamic response. Therefore, reinforced measures should be focused on cantilever strengthening when necessary.

3. REMARKS ON EARTHQUAKE RESISTANCE DESIGN OF HIGH DAMS IN CHINA

(1) The fact that no structure collapsed or caused downstream flooding in Wenchuan earthquake indicated the dams, with normal design and construction techniques, possess sufficient safety factor against strong earthquakes. The specified design criteria for high dams to resist earthquakes with 0.02 probability in return period of 100 years is considered appropriate. However, according to our new revised Design Specification for high dams to resist earthquakes (draft), a higher safety check of 0.01 probability in 100 years is required. Currently, more than 20 key projects and dams with 200+ m high in China are being checked to conform with the revised criteria.

(2) The performance of high concrete dams, i.e. the Shapai RCC arch dam and Baozhusi gravity dam are satisfied with either structured intact or only minor damage even though they are located in the region of affected intensity of VIII or above. From the follow-up investigation of Shapai arch dam, several key factors may have important effects on the satisfactory behavior of dams during the strong shaking. These include: (i) the earthquake input mechanism with considering radiation damping due to infinite canyon may significantly reduce the dam response; (ii) contraction joint opening has been found to be another important factor that may release arch action of the dam and prevent the dam from cracking. However, the disadvantages of joint openings need to be considered are the maintenance of the integrity of the dam body and prevention of waterstops between joints from breakage. The increase of tensile stresses in cantilevers due to joint openings also needs to be paid attention to.

(3) For purpose of enhancing the capability of earthquake resistance, nonlinear analyses considering damage and cracking behavior of concrete and reinforced strengthening measures are also necessary. In this case of safety evaluation, we suggest that design guideline conform with the following performance indices: (i) the grouting curtain should not be penetrated by cracking at the dam heel; (ii) cracking of the upper part of the dam body should not be completely penetrated from downstream to upstream; (iii) dam base and abutment residual deformation should not be larger than allowable value. And for arch dams, in addition to the above three indices, an additional index is that the maximum contraction joint opening should not be larger than allowable value.

(4) Currently, a series of high dams up to 200-300 m in height and hydropower plants with huge

capacity are under construction or in stage of feasibility studies in China. These cascade projects are distributed on upper to lower reaches of several large rivers such as the Jinsha river, Lancang river, Dadu and Yalong rivers etc. In this situation, an important factor of consideration is that risk assessment for cascade dam projects under a series of induced catastrophe events due to the main shock is necessary. An extremely strong earthquake may induce a chain reaction to the failure of cascade projects causing severe flooding in downstream area. Also, a serious lesson learnt from the Wenchuan earthquake is the secondary catastrophe after the main shock were unexpectedly severe, especially due to large-scale landslides, and barrier lake formation and breakage. Totally 250 barrier lakes were formed due to large-scale landslides and debris flows during the earthquake. The most severe lake was the Tangjiashan, which caused multiple disasters to the downstream Beichuan County. The county was first destroyed by the main shock (May 12, 2008), then flooded by Tangjiashan lake breakage (June 10, 2008), and subsequently buried by a large-scale debris flow (Sept. 24, 2008). Therefore, a risk assessment of an earthquake combined with secondary disasters due to chain-reaction of the main shock is necessary in the evaluation of earthquake losses.

(5) Surveillance and inspection of earthquakes at the dam site are crucial. Currently, network facilities for seismic field measurements are important for most of newly built dam sites. Also, reservoir emptying facilities, i.e. tunnels and orifices at low elevation for high dams in seismic region are necessary. Normal maintenance of the facilities is also important.

AKCNOWLEDGEMENT

The authors acknowledge the support for this research from the National Natural Science Foundation of China (Grant no.40974063) and the research funding from the State Key Laboratory of Hydroscience and Engineering, Tsinghua University (No. 2011-KY-3).

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