CONSIDERATION OF DAM SAFETY AFTER WENCHUAN EARTHQUAKE IN CHINA[1]

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ABSTRACT:

In this paper in view of the dam safety some special features of the Wenchuan Earthquake on May12,2008 in China are noted. The damages and behavior of dams, especially for the 4 dams with a height over 100m, in the area affected by the earthquake are briefly described. The lessons corning dam safety learnt from the devastating quake are preliminarily drawn. As the seismic safety of high dams during strong earthquake is the problem caused wide attention around the would, some critical problems related to the dam construction in China are considered and discussed after the Wenchuan earthquake, such as: “Why the dam construction is necessary in China as a seismic country?”, “How to evaluate the seismic safety of high dams built in the western region of China with seismogenic structures?”, “Whether the reservoir impounding of the Zipingpu and the Three Gorges Projects could trigger the Wenchuan Earthquake?”, “What is the major challenge has to be faced for Chinese dam engineers of seismic aspects?”. Finally, the corresponding tactics with response to the challenge are suggested.

KEY WORDS:

Wenchuan Earthquake: high dams: seismic safety: critical problems: challenge and tactics

1. INTRODUCTION

A devastating earthquake with a magnitude of 8.0 has abruptly occurred in Wenchuan County of Sichuan Province in China at 2:28 pm on May 12, 2008. Its epicenter located at 103.4 E and 31.0 N with a focal depth of about 15km. As Sichuan province is the province with abundant water resources and the largest hydropower potential in China, the earthquake has affected a large number of dams. Dam safety becomes one of the most serious problems concerned by not only the dam engineers but also the public both in the country and abroad. In this paper in view of the dam safety, some special features of the quake and the dam behaviors during the earthquake are briefly described. Also, the lessons learnt from the Wenchuan Earthquake and some critical problems must be seriously considered afterwards are discussed.

2. SPECIAL FEATURES OF THE EVENT IN VIEW OF DAM SAFETY

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2.1. Very Strong Intensity

It has been revealed that the causative fault of the quake is the central fault of the Longmenshan tectonic fault zone characterized by thrust with slightly dextral strike. However, due to the situation that the Longmenshan fault had a minimum deformation rate among many faults in the Qinghai-Tibet Plateau and the maximum magnitude of historical events in this area has never been over 6.5, its potential risk of suddenly releasing the long-term accumulated energy has been underestimated. The Wenchuan Earthquake is the largest earthquake to hit China in more than three decades. The magnitude and rupture scale of 5.12,2008 Wenchuan Earthquake has exceeded that of the 7.28,1976 Tangshan Earthquake and the 9.21,1999 Chi-Chi Earthquake. The shaking intensity preliminary estimated by the China Seismic Administration on May16,2008 based on field investigation, ground rupture from aero photo, distribution of aftershocks, source mechanism inversion analyses of rupture process and reference to widely used attenuation lows is much higher than that corresponding to the current 《Seismic ground motion parameters zonation map of China (2001)》 as shown in Fig.1.

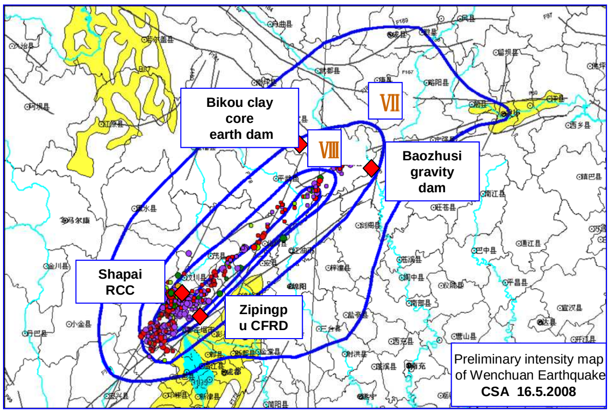

Fig.1 Preliminary intensity map of Wenchuan Earthquake

As a result, the Zipingpu concrete faced rockfill dam (H=156 m) and the Shapai roller-compacted concrete three-center gravity arch dam (H=130 m) both located near to the epicenter have the actual intensities of more than Ⅸ much more higher than their design intensities of Ⅶ and Ⅷ with design accelerations of 0.138 g and 0.260 g, respectively.

2.2. Quite long duration

The source mechanism analysis illustrated that the rupture process of the earthquake has extended along the fault from south to north east up to more than 300km. The resolved seismic source time function displays a sequence of rupture cause a quite long duration with a total interval of about 120 s as shown in Fig.2.

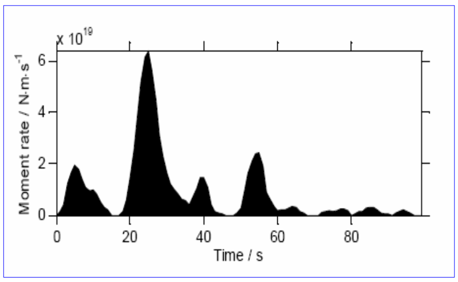

Fig.2 Seismic source time function

It is well known that the dynamic responses of embankment dam is even more sensitive to the duration of seismic input rather than to the peak acceleration as the dynamic resistance of dam materials are reduced along with the vibration duration.

2.3. Widely spread areas

The strong earthquake with long duration causes the shock to be felt at very large distance covering most areas of China. According to the statistical data from the China Ministry of Water Resources 2380 reservoirs throughout eight provinces and cities including Sichuan, Chongqing, Shanxi have been affected by the quake. Within the drainage basin of the Min River 29 hydropower plants in operation have been hit by the quake, of which 10 at the trunk stream and 19 at its tributaries.

2.4. In the mountain area with fragile rock stratum

As well known that the Indian plate dives to the Asian plate, causing fast uplift of the Qinghai-Tibet Plateau. The plateau materials slowly move to east, crushed eastward along the Longmenshan structure zone on the eastern edge of the plateau. The movement is blocked by the rigid table under the Sichuan Basin to arouse large fault belt and eventually to cause the Longmenshan fault as the causative fault of the Wenchuan earthquake. In addition, the rock stratum in this mountain area with active tectonic movement is also rather fragile. So, many massive landslides and mudflow have been induced by the strong earthquake to form a series of barrier lakes along the rivers.

3. DAMAGES AND BEHAVIORS OF DAMS

The Chinese seismic design code of hydraulic structures adopts the widely used concept of designing structures to allow repairable damage in maximum design earthquake (MDE). Obviously, as earthquake is a powerful natural force, it is neither unlikely nor economical to design all structures to perform without damages in an extreme event like the Wenchuan Earthquake. After the earthquake many teams with a number of experts have immediately been dispatched to the earthquake-hit region to check the damages of dams and to provide professional instructions for dealing with the emergency situations of the dams.

3.1. A large number of small-medium dams

Sichuan Province is rich in water resource and hydropower potential and has a large number of reservoirs as mentioned above. It is the most important hydropower energy base of China. A total of 1803 dams were reported to be damaged to different extent during the devastating quake. But most of them (about 95%) are small homogeneous earth dam for water supply and irrigation with a storage capacity less than 5Mm^3. The main damages of these dams during the quake are cracking, slop sliding, crest settlement, leakage, failure of spillway and outlet, and so on. Fig.3 shows one of the damaged dams with crest cracking.

The famous Dujingyan irrigation system which has supplied water to Sichuan's fertile eastern plains for more than 2,000 years is safe during the destructive quake; even it is located quite near the epicenter. Only small cracks of (2-3) cm on the weir surface (Fig.4) and local damage at the support of the headstock gear for sluice were detected.

In the high mountain areas with steep gorges of the Min River most hydropower projects are of diversion type with small reservoirs and low concrete dams which are more resistant to seismic loading and overtopping than embankment dams.

However, some dams were at high risk of collapse. Luckily, most reservoirs were not full in this pre-flood period. The emergency measures of lowering the reservoir water level in time through equipped spillway or outlet to avoid dam collapse appeared quite effective. The power generation facilities of some hydropower plants like Shapai, Taipingyi, Yingxiuwan, etc. were heavily damaged, but their dams were safe even with overtopping.

The Three Gorges Project and the high Ertan arch dam (H=240 m) have no impact from the quake, as they are located several hundred kilometers away from the meizoseismal area.

Fig.3 Damaged small dam with crest cracking

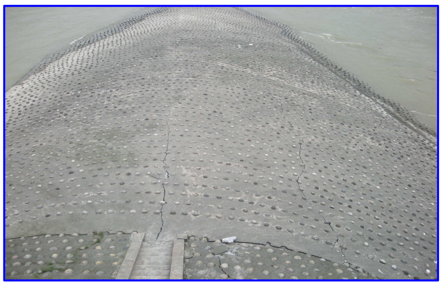

Fig.4 small cracks of (2-3) cm on the Dujiangyan weir surface

3.2. Four high dams of different types with a height of more than 100m

In the quake-hit area with intensity of more than Ⅶ there are only 4 high dams of different types with a height of more than 100 m.

3.2.1 Zipingpu concrete faced rockfill dam

Zipingpu CFRD of 156 m high was completed in 2006. It is located upstream of Dujiangyan City in the region with an epicentral distance of about 17km and an intensity of more than Ⅸ far over its design value. During the earthquake the reservoir had a minimum water level at EL 817m with a reservoir volume of only 0.2 billion m^3 while its normal water elevation is 884.0 m with design reservoir volume of 1.1 billion m^3.

After earthquake the maximum settlement of 734.6 mm at dam crest and the horizontal deflection to downstream of 179.9mm have been measured. The cross canyon deflections of both banks are pointed to the river with a total value of 101.6mm to squeeze the dam. The face slabs were partially dislocated along the construction joints and broken away from the bed course with a maximum bulge of about 150 mm (Fig.5). Cracks between road at crest and downstream slope protection have obviously appeared (Fig.6).

Fig.5 Damages of face slabs

Fig.6 damages of downstream slope protection

The concrete slabs and the peripheral joints were slightly deformed. But after the shock an anomaly share deflection up to 104.24 mm at the base of canyon has been detected, however, the malfunction of the transducer can not be excluded so far. As the change of seepage is only ranging from 10.38l/s before the shock to 15.07l/s after the shock. It seems that even if the sealing copper sheet might be damaged, the surface water stop system including the clay overburden still keeps in normal order. Some parapet walls and banisters at crest were collapsed

The sluice gate building and multi-functional facility suffered a range of damage during the earthquake.

3.2.2 Saipai roller-compacted arch dam

Saipai dam of 130 m high completed in 2006 is the world's highest RCC arch dam at that time. The dam is a three-center gravity arch structure having a crest length of 250.25m. It is 9.5m thick at the crest and 28m at the base. The dam is located 30km away from the epicenter and the reservoir kept its normal water level of 1866.0m during the quake. There are two contraction joints and two induced joints along the arch direction. The dam is founded on granite and granodiorite formations making up the relatively steep-walled and V shaped canyon. The dam abutments are supported by rock mass of class Ⅱ without continued plane of weakness. The seismic design of the dam has been carried out with a design peak acceleration of 0.138g corresponding to a return period of about 500 years based on a special seismic hazard analysis for the dam site. The dynamic responses of the dam were checked both by dynamic trial method and finite element method. The dam site is still not accessible due to the road blockage by the landslides so far. However, base on the aerial photo and report from individual investigator entered by walking, it revealed that the dam including its anchored abutments is stable without evident damages (Figs.7-8). But the power plant has been inundated due to the collapse of the partial penstock being across the river.

Fig.7 Aerial photo of Saipai dam

Fig.8 Left and right abutment of Saipai dam

3.2.3 Baozhusi concrete gravity dam

Baozhusi concrete gravity dam of 132 m high with reservoir volume of 2.55 Mm^3. The seismic safety of the dam was checked with a design intensity of Ⅶ. The intensity of the dam site during the Wenchuan Earthquake is about Ⅶ-Ⅷ. An aftershock of magnitude 6.4 has occurred in Qingchuan County about 20 km away from the dam. No damage of the dam or abnormal change in uplift pressure and leakage of the foundation were detected by the inspection carried out after the quake. The leakage water became a few muddy after the quake, but returned to normal after two days.

Up to now around the world there are only 3 dams of gravity type subjected to strong earthquake of intensity more than Ⅷ. They are the Koyna dam in India, the Hsinfengkiang dam in China, and the Sefid Rud dam in Iran. All those dams were cracked in upper part across the whole section near the break point of the downstream slope. Probably, the following favorable factors make the Baozhusi dam more seismic resistant during the Wenchuan Earthquake, such as: all contraction joints have interlocked keys and were grouted at lower part; its reservoir kept the minimum level of EL 558m during the quake; the main component of seismic action were along dam axis, as verified by the fact that the claw beams of gate at the crest were moved in 20cm along the dam axis.

3.2.4 Bikou clay core embankment dam

Bikou clay core embankment dam of 105.3m high with reservoir volume of 0.5 Bm^3 is located in Gansu province, a neighboring province of Sichuan.. The dam was completed in 1976. The actual intensity of dam site is close to its design value of Ⅶ-Ⅷ. No other damage has been reported except to have 30cm displacement at the crest.

3.3. Barrier lakes

So long 35 barrier lakes had been reported in the quake-hit areas. Since the barrier lakes seriously threaten both upstream and downstream areas, it became the major dangers of the secondary disaster of the earthquake especially while considering the followed-up aftershocks and flood season. River water overflowed three of the barrier lakes in Qingchuan County, but posed no damage. All the dangerous barrier lakes have been monitored and under controlled. The most dangerous Tongjiashan barrier lake located about 6 km away from the Beichuan County measured 803m long, 612m wide and80-125m high with a volume of 20Mm^3. Emergent measures have been taken to remove the blockage from the river course by excavating discharge canal as wellas to evacuate the downstream resident. The dangerous situation has been successfully got rid of.

Until now the investigation is being continued even the roads to some dam sites are still not accessible to closely inspect. All relatively high dams are being required to have re-examined after the quake. However, some preliminary conclusions can be drawn as follows:

(1) The safety of all dams including the natural dams of barrier lakes has been under controlled and no single dam was breached.

(2) All four high dams of different types with a height of more than 100 m including the Saipai RCC arch dam and the Zipingpu CFRD in the epicenter area have been structurally stable and safe.

4. LESSONS CONCERNING THE DAM SAFETY LEARNT FROM THE EVENT

(1) As "practice is always the unique criterion for checking truth", the thorough in-situ investigation and the deep studies on it quickly after the devastating earthquake like in Wenchuan are of extremely necessary to improve the future seismic design ideas and Code as well as to continue advancing studies in the field of seismic safety of dams.

(2) As earthquake is powerful natural force, it is neither likely nor economical to design the dam structures to perform without any damage in a devastating quake. From the Wenchuan Earthquake it was revealed that despite the mismatch of the design intensity and the actual intensity for dams located near the epicenter like Zipingpu and Saipai dams, their integral structural stability and water retaining function were still remained even with some repairable damages. It might be concluded that for dams well designed according the current cord and good constructed, their desired seismic safety would be basically anticipated.

(3) Considering the uncertainties of seismic input as shown in the Wenchuan Earthquake and the complexities of high dam structures of different types as well as the catastrophic aftermath of their secondary disaster, it is of extremely importance to prevent any collapse of high dam under the actions of so called "maximum credible earthquake (MCE)". For critical high dams this requirement should be included into the framework of the revising seismic design cord in addition to the "maximum design earthquake" with performance objective of repairable damage.

(4) The geological stability of dam foundation under strong seismic action cannot be overemphasized especially for arch dams. It is still impressed the major damages mainly due to the weak left abutment of the Pacoima dam during the 1971 San Fernando and the 1994 Northridge earthquakes. The satisfactory behavior of the anchored high slopes in the areas of Zipingpu and Saipai dam abutment during the Wenchuan Earthquake manifested the effectiveness of the engineering strengthening measures; even the neighboring slopes were heavily damaged.

(5) The emergency lowering reservoir water was the most effective measure to prevent the secondary disaster of dam during the Wenchuan earthquake. In the emergency response plan scenario for destructive earthquake a great importance should be attached to the reliability of the emergency discharge structures and facilities as well as their energy supply under strong seismic actions.

(6) The fact that the new type high dams like the Zipingpu CFRD and the Saipai RCC arch dam have stood a severe test of the strong Wenchuan Earthquake is quite meaningful as more such kind of high dams will be constructed in China and abroad. But even some high dams near the epicenter were structurally stable during the strong Wenchuan earthquake; however, we must not in no way be off our guard and become careless. There might be essential changes in dynamic behaviors while the height of dam upgrade to a level of 300m like in the case of high dams under construction in the Western China.

5. Some critical problems concerning seismic dam safety in China

5.1. Why the dam construction is necessary in China as a seismic country?

Water and energy and the affected environment are key factors constrain the economic development and environmental improvement of China. The reasonable allocation of the scarce water resources to guarantee water supply and to prevent flood and draught disasters as well as the effective utilization of the abundant renewable and clean hydropower potential ranked the world's first are the arduous task for sustainable economic development and assured environment's security in China. Dam construction plays an important role to adopt the condition of country for accomplishing the task.

China is also a country with high seismicity especially in the western region where no other than concentrated about 80% of the national total hydropower resources. So, the seismic safety of high dams is an inevitable challenge we have to face.

5.2. How to evaluate the seismic safety of high dams built in the western region of China with seismogenic structures?

Though the earthquake prediction is a world's difficult problem not solved as yet; the capital construction including dams still have flourished in seismic regions all over the world. Of course, the studies both on seismic hazard assessment and seismic design of dams have never interrupted and continuously advanced to improve the seismic safety of dams. Until now in the world high dams have damaged due to strong earthquake but have no single breached yet while building collapse and landslides have often killed thousands; as illustrated in Wenchuan Earthquake too.

5.3. Whether the reservoir impounding of the Zipingpu and the Three Gorges Projects could trigger the Wenchuan Earthquake?

As well know; only less than 1% of reservoirs on a global scale have reported to have the “reservoir earthquake”. The mechanism of reservoir earthquake is not clear also as for the natural earthquake. However, its more commonly accepted explanation is that the pore pressure of the reservoir water permeated into rock reducing its effective stresses and causing the drop of shear resistance is the major factor rather than the added impounding water weight negligible in comparison with the weight of rock in depth. There are two kinds of the reservoir earthquake. The nonstructural one linked to the karst, mine pit, and stress readjustment at the shallow surface layer usually produces reservoir earthquakes with magnitude less than 3-4. So far most of reservoir earthquakes are belong to this kind. The structural one linked to the causative faults near the reservoir can only trigger reservoir earthquake with magnitude not exceeding what is indigenous in the fault; if its existing stress are close to failure.

The flood water level of the Min River at the Zipingpu reservoir edge nearest to the Longmenshan fault causing the Wenchuan earthquake is at EL884m while the maximum reservoir water level has never exceeded EL875m. During the earthquake the reservoir located at the lower wall of the longmenshan fault had a minimum water level at EL 817m. Clearly, there is no hydro-geological condition for the reservoir to trigger the Wenchuan earthquake. Besides, a special seismic monitoring system for reservoir earthquake has been set up in August 2004. The impounding of the reservoir started in October 2005. The variation of the recorded seismic activity including the occurrence frequency and magnitude before and after the reservoir impounding appeared in a normal range. There is no reservoir earthquake in Zipingpu Project at all.

The Wenchuan is located far away from Three Gorges project; moreover, there is no any tectonic structure connection between them.

Furthermore, in the Wenchuan event there was no any forerunner earthquake as a special characteristic of the reservoir earthquake. The highest magnitude triggered by reservoir, to date, is 6.3. Obviously, neither the Zipingpu nor the Three Gorges reservoir impounding could trigger the Wenchuan Earthquake. Also, the Wenchuan Earthquake is not provided with the basic characteristics of reservoir earthquake.

5.4. What are the major challenge we have to be faced and the corresponding tactics adopted?

As any accident of collapse of high dam with huge reservoir during strong earthquake can inflict grave secondary disaster upon surrounding communities, to prevent such seismic catastrophe is the major challenge we have to be faced. Therefore, the behaviors of the dam during the MCE at dam site must be clarified and the uncontrolled release of the reservoir water should be avoided. However, neither engineering practice all over the world nor lessons from past earthquake cases can be used for reference to ensure seismic safety of extra high arch dams which are being and will be constructed in severe seismic areas of China so far.

Facing the severe challenges, we have to overcome the major obstacles to assess the seismic catastrophe of high arch dams, focusing on the clearly defining the MCE and reasonably selecting its site-specific seismic input parameters as well as on the criterion quantitatively evaluating the limit state of dam-breach for designer.

Our conclusion is that the high dam construction is necessary and feasible even in the seismic regions of Western China considering the situation of the country. However, we have to make increasing progress in practice of dam construction through further investigations and hard studies on the seismic safety, but never “give up eating for fear of choking”. Also, we are looking forward to have more opportunities for further international cooperative research on seismic safety of high dams with all colleagues.

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