



Zipingpu dam

# The relationship between large reservoirs and seismicity

*Following the 12 May 2008 Wenchuan earthquake in China, Chen Houqun, Xu Zeping and Li Ming discuss the question of whether large reservoirs can trigger strong earthquakes*

**T**HE issue of reservoir-triggered seismicity (RTS) received a great deal of attention worldwide following the earthquake which jolted Wenchuan County in Sichuan Province on 12 May 2008, resulting in the death of over 60,000 people. A major question raised was whether the earthquake was related to the impoundment of the nearby Zipingpu reservoir – or even the Three Gorges reservoir. There are a number of different views on this issue and the authors believe the ongoing discussion will emphasize the importance of the seismic safety of dams, while promoting further research on the subject.

## GENERAL CONCEPTS OF RESERVOIR TRIGGERED SEISMICITY

Seismic events have occurred near large dam sites or in reservoir areas, and may have been triggered by changes in the physical environment as a result of impounding and operation of reservoirs.

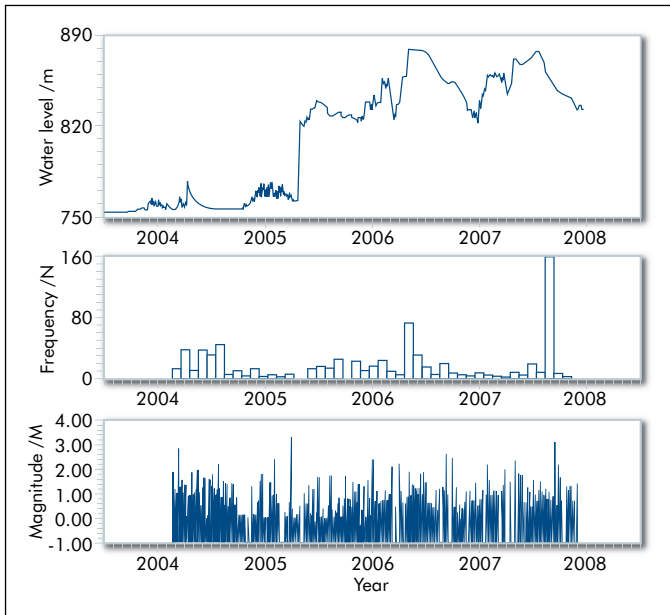
For example, seismicity was observed following the 1929 impounding of the Marathon reservoir in Greece (dam height of 60m). Earthquake activity was also observed in 1935 after the impounding of the Hoover dam in the US (dam height of 220m). Since then, over 100 large dams may have experienced RTS. There are still disputes however as to when RTS has actually occurred.

In the ICOLD Bulletin on Reservoirs and Seismicity – State of Knowledge (Bulletin 137, 2009) prepared by ICOLD's Committee on Seismic Aspects of Dam Design, 39 cases of RTS are presented. Considering this, the number of RTS cases worldwide is very small compared to the total number of reservoirs worldwide – with RTS suspected in a higher portion of large dams. Most RTS events are small magnitude events. However, there are a few cases with magnitudes exceeding 5. So far, there are four major RTS events with a magnitude over 6.0. They are: (i) 103m high Koyna gravity dam in India (M=6.3); (ii) 120m high Kremasta embankment dam in Greece (M=6.3); (iii) 105m high Hsinfengkiang buttress dam in China

(M=6.1); (iv) 122m high Kariba arch dam in Zambia (M=6.25). The highest observed earthquake magnitude was 6.3.

The complicated mechanisms of RTS are not well understood and may differ from case to case. The main reasons for this are the very limited knowledge of the rheology of crustal material and groundwater movement under high pressures and high temperature conditions in the hypocenter region. Therefore, in the absence of instrumental data, it is difficult to establish and calibrate a physical model to describe this complicated process. At present, this is studied using statistical methods, computer simulations, and increased monitoring of areas where RTS has been observed. The following two types of earthquakes associated with reservoirs can be distinguished:

- (i) Earthquakes of non-tectonic nature with shallow focus, which are mainly related to stress adjustments in the foundation rock, collapse of karst caves and mining tunnels, and mass movements. These events of relatively small magnitude often occur shortly after reservoir impounding or following sudden reservoir water level fluctuations. Generally, on the basis of existing case histories, these earthquakes have magnitudes of less than 5 and are not harmful to dams and the reservoir area.
- (ii) Earthquakes of tectonic nature (referred to as RTS) caused by seismogenic faults passing through or adjacent to the reservoir area. The initial stress state must already be very close to failure so that a minor change in stress or minor change in strength properties in a fault plane caused by the water in the reservoir could trigger seismic events. The epicenters of the foreshock with small magnitude of this kind of earthquake are usually clustered around seismogenic structures. The magnitude of RTS events may gradually increase until the main shock occurs. Following the main shock, the aftershocks normally last for a certain period. As the process of reservoir water infiltration into the rock stratum takes time, there is normally a time lag between the main shock and when the reservoir water reaches its highest level. However, depending on the local conditions, different foreshock, main shock and aftershock patterns are possible.



**Figure 1: Water level in the reservoir (top) and seismic activity observed in Zipingpu reservoir are (N: number of events; M: magnitude)**

The magnitude of the main shock is the main concern for dam engineers. Until now, the four RTS earthquakes with magnitudes over 6.0 belong to this foreshock-main shock-aftershock type. This kind of RTS event is a major concern for engineers.

In the studied literature, these two types of earthquakes are also considered as endogenous and exogenous reservoir earthquakes.

The accumulation of strain energy of tectonic earthquakes originates from the seismogenic structure of the earth. It is the potential seismic source irrespective of the existence of a reservoir. Compared with the huge amount of energy released by a strong earthquake, the impact of reservoir impounding on the strain energy of the seismogenic faults is very small. The impounding of a reservoir can only trigger an earthquake when the accumulated strain energy of the seismogenic fault is close to the critical stress state.

The total seismic energy includes the following parts: fault rupture energy, wave radiation energy, and heat caused by friction and inelastic processes. The intensity of earthquake ground shaking depends on the energy transferred by earthquake wave radiation. The energy of seismic waves is measured in terms of magnitude. Theoretically, the maximum magnitude of RTS events is determined by the upper bound magnitude of the seismogenic faults. No earthquake can be triggered by a reservoir with a magnitude higher than that of the spontaneous earthquake. As for the determination of the upper bound magnitude, the commonly applied methods in China include: (1) the method based on historic earthquakes and tectonic structure, (2) the method based on paleo-earthquake and statistics of active fault parameters and, (3) the method of synthetic structure analogy.

It is still not entirely possible to reliably predict strong earthquakes, and the present methods to determine the upper bound magnitudes of seismogenic faults are imperfect. The Wenchuan earthquake occurred at the section of the Longmenshan Fault where the historically recorded seismic activity is relatively low. However, it has the most significant compression deformation and stress concentration. The Longmenshan Fault has the lowest long-term deformation rate compared with the other major faults of the Qinghai-Tibetan plateau, and the recorded maximum magnitude in this area was 6.5. In general, the understanding of the seismotectonic processes of low-activity faults – which have a long-time energy accumulation that could finally lead to a strong earthquake – is limited. After the Wenchuan earthquake, seismological and geophysical experts reanalyzed the related data and increased the upper bound magnitude of the Yinxiu-Beichuan fault area from 7.0 to 8.0.

Although seismological and geophysical experts have conducted



many studies and investigations and have carefully determined potential seismic sources and their upper bound magnitudes, you cannot exclude the possibility that the maximum historically recorded magnitude could be exceeded. This is an important problem in the assessment of seismogenic faults, irrespective of whether there are reservoirs or not.

Although the role of the water in the reservoir hydrogeology for RTS still needs further studies, it is widely accepted at present that the infiltration pore pressure and the added weight of the reservoir water are the main factors affecting any seismicity patterns. Obviously, even for a dam storing a reservoir with a depth of over 100m, the impact of the added weight of the reservoir water on the crustal stress field near the hypocenter – which may be located at a depth of more than 10km – is negligible in comparison with the deadweight stresses of the rock mass. But when water from the reservoir infiltrates into the rock mass at the depth of several kilometers, the pore pressure will reduce the effective stress and the shear strength parameters in the fault will be reduced. Thus the total shear strength of the fault is reduced and may initiate a crack propagating along the faults and thus trigger an earthquake. Such a model is well understood by dam engineers, although the water infiltration process is still unclear and the mechanical properties of the crustal materials at a depth of say 10km, as well as the initial stress state originating from the underlying tectonic processes, is unknown. Based on the concept of water infiltration the following factors for triggering RTS events may have to be considered [4]:

- As the impact of reservoir impounding on the crustal stress field at the source of earthquake is very small when compared with the stress field of the seismogenic fault, the reservoir impounding can only trigger an earthquake which is already at critical condition.
- For RTS to occur, certain seismic and hydro-geological conditions must be satisfied, which include: (1) the existence of seismic structures in or adjacent to the reservoir area, (2) the seismic structure is close to failure before reservoir impounding, and (3) the existence of the hydrogeologic condition for the infiltration of reservoir water into the deep rock stratum.

Obviously, there are very few large reservoirs that possess such conditions. This is the reason why only a few cases of tectonic reservoir earthquakes with high magnitude has occurred at the many high dam projects constructed around the world.

In fact, a reservoir-triggered earthquake (RTE) has no substantial difference from a spontaneous earthquake. The magnitude of its main shock could not exceed the upper limit magnitude of the spontaneous earthquake of the fault. The process of reservoir water infiltration causes a time lag between the reservoir impounding and the occurrence of the main shock of RTS. The focal depth of RTE is relatively shallow.

The area affected by reservoir water infiltration cannot exceed the first dividing ridge between valleys where the ground water table exceeds the reservoir level. This could determine the spatial distribution of RTS.

As for the type of fault, from the analysis of the impact of reservoir water on the stress state of the fault plane, the strike slip and normal faults are more prone to be triggered compared with thrust fault [7].

Thus far, the seismogenic faults of the four major RTE with magnitudes larger than 6.0 are all normal or strike slip faults [9][10].

Based on the above analysis and statistics of the available cases of RTS, the general principles for estimating the relationship between an earthquake and reservoir impounding can be summarized as follows:

- To investigate if there is a correlation between the time of reservoir impounding or reservoir water level variation, and the occurrence of earthquakes. Normally, the frequency and intensity of small earthquakes will increase significantly when compared with the background seismicity of the area before the construction of the dam, and it is often correlated with the impounding or variation of the reservoir water level. After the reservoir has reached its highest level, or the main shock has occurred, with the adjustment of rock mass stress in reservoir area, the activity of the earthquakes in the reservoir area will gradually return to the background state.
- The epicenters of reservoir-triggered earthquakes should be located within the area affected by water infiltration along the fault zone. The epicenter is normally thought to be located in the range of 5-10km away from the edge of the reservoir. The epicenters of non-tectonic earthquakes are scattered in groups and correspond to the locations of karst caves or mining tunnels. For the analysis and assessment of reservoir-triggered (tectonic) earthquakes, besides the distribution of epicenters and the variation tendency of intensity, additional monitoring data should be collected. The occurrence of reservoir earthquakes requires a special geological environment. Either the reservoir area has the seismogenic structures that may lead to tectonic earthquakes and also the hydrogeological conditions to allow reservoir water to infiltrate deep rock stratum, or it has fractured rock mass, karst caves and mining tunnels that may lead to non-tectonic earthquake activity. It should be noted that not all the faults are pervious – some old faults may be impervious. Therefore the condition of faults also needs to be analyzed.
- When comparing the characteristics of tectonic (RTE) with spontaneous earthquakes, the focal depth of RTE is usually shallow. The ground shaking attenuates rapidly with the distance from the seismic source. The non-tectonic earthquakes occur generally as small earthquake swarms. The RTE normally has a foreshock-main shock-aftershock pattern. The four main cases of RTE with magnitudes larger than 6.0 belong to this type. The magnitude ratio of the main shock to the maximum aftershock is high. The b-value in the magnitude-frequency relationship ( $\log N = a - b M$ ) is also high. The dominant frequency of the ground acceleration and the ratio of the vertical and horizontal earthquake components are all relatively higher. For the same magnitude, the reservoir-triggered earthquake may have a stronger surface shaking than a spontaneous earthquake [7, 8].

When assessing the possibility of RTS, you should first determine the seismogenic regions where earthquakes could occur. The judgment should be based on the main impact factors, such as the activity,

state and magnitude of the faults in the reservoir area, the seepage conditions for reservoir water infiltration into deep rock stratum, dam height, reservoir storage capacity, rock properties and the development of structure planes and karst phenomena in the reservoir foundation, etc. The maximum magnitudes of the different reservoir segments are mainly determined by referring to existing case histories of reservoir earthquakes and to follow the principle of engineering analogy. According to the main impact factors, the probability of different magnitude intervals can be determined from methods such as: experienced discrimination, statistical hazard evaluation, grey clustering, fuzzy estimation, and artificial neural network, etc.

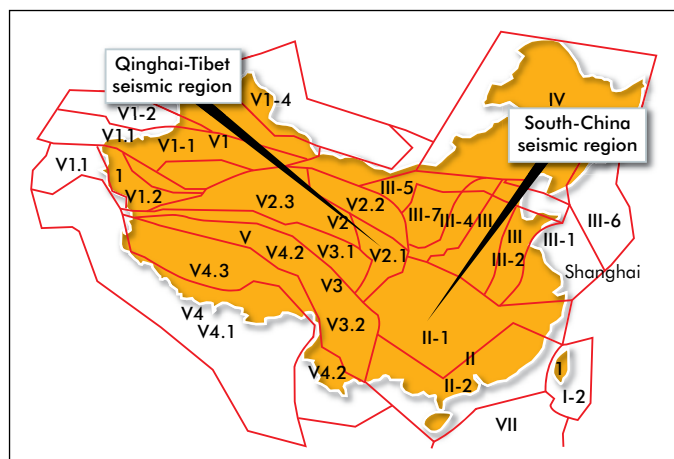
Since the occurrence of the strong reservoir-triggered earthquake in the Hsinfengkiang reservoir in 1962, Chinese dam engineers have given greater importance to the problems of RTS. Deciding whether an incident is RTS is mainly achieved by comparing the seismic activity monitored before and after reservoir impounding. Therefore, according to the Seismic Design Code of Hydraulic Structures in China, for reservoirs with a dam height of over 100m and a storage capacity of over 50Mm<sup>3</sup>, if RTS events with intensity over VI (Chinese intensity scale is very similar to the MMI scale) are estimated, a special seismic monitoring network with high precision seismic sensors should be installed before impounding to obtain the proper background data. For both the Xiaolangdi and Zippingpu projects, a seismic monitoring network was installed before reservoir impounding. A digital remote monitoring network for observing RTS – the first in China – was also set up prior to impounding of the Three Gorges project. This system includes 24 fixed stations, three relay stations, a network center, eight movable stations, and two non-remote stations.

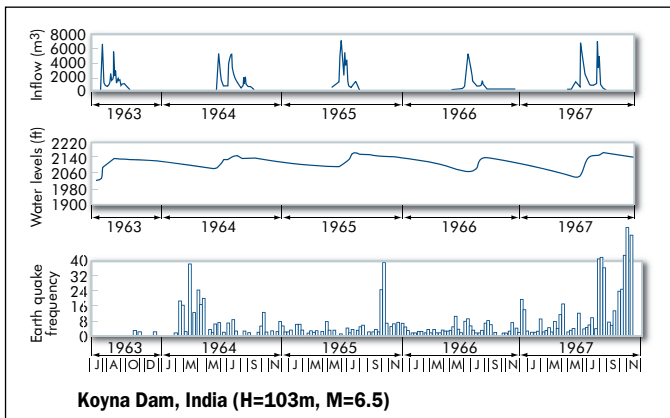
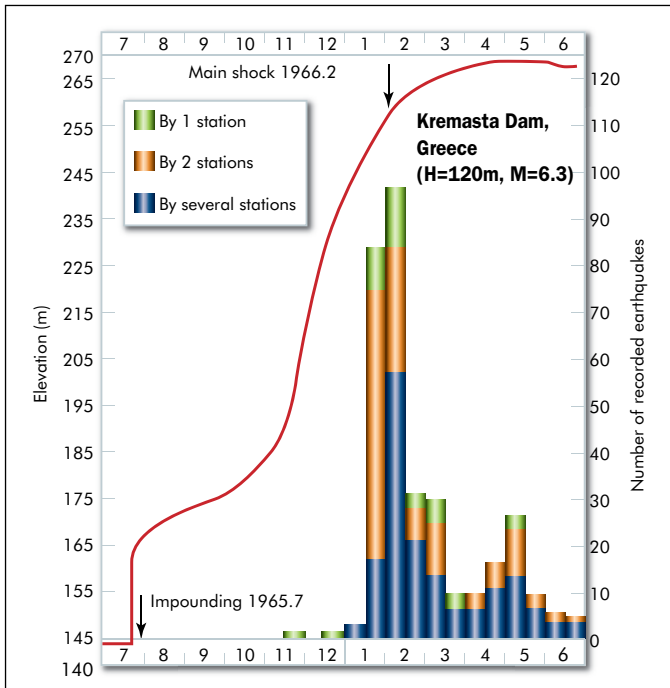
More recently, construction began on a microseismic monitoring network of unprecedented scale in the reservoir areas of the four cascade hydro power projects in the lower reaches of the Jinshajiang River. This will include 62 fixed stations and eight floating stations.

### ZIPINGPU AND THREE GORGES

*Could the impounding of Zippingpu trigger the Wenchuan earthquake?* Zippingpu reservoir is located between the Beichuan-Yinxu fault and the Jiangyou-Guanxian fault of the Longmenshan fault zone. The shortest distance from the southwestern branches of the reservoir tail is about 4.5km away from the epicenter of the 12 May 2008 Wenchuan earthquake. The maximum water level of the Zippingpu reservoir (elevation 875.4m asl) has not exceeded the natural water level (elevation 877m asl) where the Min River crosses the Beichuan-Yinxu fault before reaching the northwestern branch of the reservoir tail, and the maximum reservoir level is even lower in the flood season when the Min River can reach elevation 884m asl. When the Wenchuan earthquake occurred, the water level of the Zippingpu reservoir was at elevation 826m asl, which is near the minimum operating water level of the reservoir. Furthermore, the Zippingpu reservoir is located in the relatively stable geological region of the footwall of

Below, left: Figure 2 – The seismic zone in China and adjacent area; Right: Dam experts checking an earthen dam following the Wenchuan earthquake





the seismogenic thrust faults. Therefore, the original hydrogeological conditions of Beichuan-Yinxu fault could not be affected by the impounding of the Zipingpu reservoir.

*Seismic activity of the reservoir area before and after impounding*

In August 2004, 13 months before reservoir impounding, the microseismic network with seven fixed stations was set up. On 27 September 2004, one of the two diversion tunnels was closed. The reservoir water level rose from elevation 752m asl to elevation 775m asl. On 30 September 2005, the second diversion tunnel was closed. Reservoir impounding started and the water level rose rapidly. In October 2006, the reservoir water level reached elevation 875.4m asl, 1.6m below normal storage level. The corresponding reservoir volume was 900Mm<sup>3</sup>. In July 2006 and May 2007, the water level was lowered to elevation 820m asl. Before the Wenchuan earthquake (30 April 2008), the reservoir water level was at elevation 828.95m asl, and the reservoir volume was 300Mm<sup>3</sup>. From the statistics of the annual seismic activity of the reservoir obtained from the Department of Reservoir Earthquake Research of the Sichuan Seismological Bureau, the frequency and intensity of seismic activity after impounding of the Zipingpu reservoir was in the normal variation range of the seismic activity recorded before reservoir impounding. The seismic activity remained almost unchanged before and after reservoir impounding. The recorded seismicity also has no relation with the reservoir water level variation. After reservoir impounding, no significantly increased seismicity was observed.

Recently, a case study of Zipingpu reservoir by Lei et al. was pub-

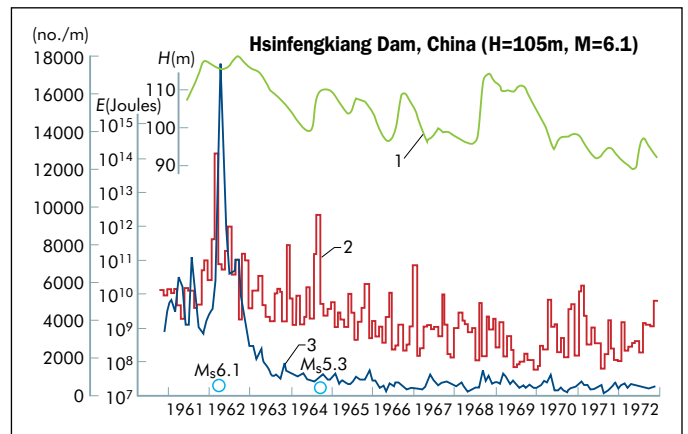
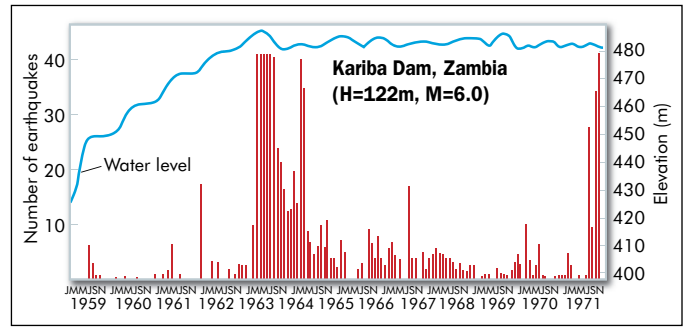


Figure 3: The relation of reservoir earthquake and reservoir water level for the four strong tectonic reservoir earthquake cases

lished in Seismology and Geology in China and was quoted by Kerr and Stone in a paper entitled ‘A Human Trigger for the Great Quake of Sichuan?’ [2, 3]. In this study, an oversimplified two-dimensional model is used with the assumption that the whole Zipingpu reservoir is located on the fault. Actually, only the narrow portion of the Ming River is located directly above the fault. Moreover, only a very small change in the fault stresses has been calculated in this simple model, which did not account for the large uncertainties in the properties of the crustal materials and the water at hypocenter depth with high temperature and pressure (>400°C and 5kPa). It is also mentioned that an earthquake of M=8 can be triggered by small changes in stresses and strength, which is difficult to be verified as the initial stress state and strength properties in the seismogenic fault of the Wenchuan earthquake are not known. Furthermore, as shown in this paper, even though the stress and strength changes induced both by the pore pressure and added weight of the reservoir water are negligible at a depth of 5-7km, the hypocenter of the Wenchuan earthquake has a depth of about 15km.

Therefore, it can be concluded that there is no observational evidence or factual investigations that the Wenchuan earthquake was triggered by the Zipingpu reservoir.

*Could the Three Gorges reservoir impounding have triggered the Wenchuan earthquake?*

Firstly, the Longmenshan Fault and the reservoir of the Three Gorges project are located in different seismic regions. They have no regional tectonic connection. The Longmenshan Fault is located in the Longmenshan seismic zone of the Qinghai-Tibet seismic region, while the Three Gorges reservoir area is located in the middle and lower Yangtze River seismic zone of the South China seismic region.

Secondly, the distance from the epicenter of the Wenchuan earthquake to Chongqing city, where the tail of the Three Gorges reservoir is located, is more than 300km, and the distance from the epicenter of the Wenchuan earthquake to the dam site is over 700 m. In October 2001, almost two years before the first stage reservoir impounding, the digital remote reservoir earthquake monitoring system with 26 stations was set up. The monitoring data showed that the frequency

of small earthquakes had increased. However, site investigations revealed that most of the earthquakes occurred at the location of karst caves and in mining tunnel areas. The earthquakes were all small shallow earthquakes with maximum magnitudes of 3.0 - 4.0. The observations from the microseismic network have demonstrated the non-tectonic nature of these reservoir earthquakes.

Moreover, there is a very thick impervious rock layer in the Three Gorges reservoir area. Therefore there is no leakage problem in the reservoir area and there is no possibility of the reservoir water infiltrating a fault zone at a distance of several hundred kilometers.

Therefore, it is obvious that there is no possibility the impounding of the Three Gorges reservoir could have triggered the Wenchuan earthquake.

### NO CHARACTERISTIC FEATURES OF RESERVOIR-TRIGGERED EARTHQUAKES

As mentioned in the previous section, the main reservoir-triggered earthquakes normally belong to the type with a distinct foreshock-main shock-aftershock pattern. The four strongest reservoir-triggered earthquakes with a magnitude larger than 6.0 belong to this type (Figure 3) [6]. Their seismogenic faults are normal faults or strike slip faults that are relatively easily triggered by reservoir water [9, 10]. The general situations of these four cases are as follows:

- (i) Kremasta: From 1700 to 1965, the Kremasta area in Greece had no significant earthquakes. After reservoir impounding in July 1965, 740 earthquakes occurred in an area of 100km<sup>2</sup>, this was followed by the main shock with a magnitude of 6.3. The seismogenic fault was a normal fault.
- (ii) Koyna: The impounding of Koyna reservoir began in the rainy season of 1962. In 1963, the earthquake activity increased. In 1964, when the reservoir water reached 100m, an earthquake of magnitude 5 occurred at the dam site. In September 1967, there were two earthquakes of magnitude 5. Three months later, the main shock of magnitude 6.3 occurred. Many experts are of the opinion that the seismogenic fault is a strike slip fault.
- (iii) Kariba: The Kariba reservoir in Zambia has a storage capacity of 153Bm<sup>3</sup>. The maximum water depth in the reservoir is over 80m. There were no seismic stations in the area before reservoir impounding, and it was thought the area had no earthquake activity. After reservoir impounding in December 1958, earthquake activity increased. In September 1963, there were six earthquakes with a magnitude over 5.0. Then the main shock of magnitude 6.0 occurred. Investigations discovered that the area has the background of a normal fault with stress state in critical conditions.
- (iv) Hsinfengkiang: The Hsinfengkiang reservoir was impounded in October 1959. One month later, earthquakes with magnitudes of 2.0 - 3.0 occurred. After nine months, the frequency and intensity of earthquakes increased substantially. In September 1961, when the reservoir was nearly full, the activity of earthquakes became more and more intense. The main shock occurred in March 1962. The earthquake activity shows a typical foreshock-main shock-aftershock pattern. The seismogenic fault is a strike slip fault.

The Wenchuan earthquake has no characteristics of the earthquakes above, which are assumed in literature as being reservoir-triggered earthquakes.

For the four reservoir-triggered earthquakes, the b-value of foreshocks is 1.0-1.87. It is obviously higher than the b-value of the spontaneous earthquake in the respective area, which was in the range of 0.47 - 0.84 [7].

The main shock of the Wenchuan earthquake occurred on the dextral obduction-type fault zone and the hypocenter depth was 15km. The earthquake has a main shock-aftershock pattern.

### CONCLUSIONS

Based on the review of the mechanisms for RTS, the worldwide experience with dams experiencing RTS, and the discussion of the Wenchuan earthquake, the following conclusions can be drawn:

- (1) The cases of RTS are very few compared to the total number of large reservoirs in the world.
- (2) Two types of earthquakes associated with reservoirs must be distinguished: (i) the non-tectonic earthquakes linked to the karst caves, mine pit, and stress readjustment at the shallow surface layer usually with magnitudes less than 3-4, and (ii) tectonic earthquakes linked to nearby causative faults with existing stresses close to failure and triggered by the water in the reservoir with magnitudes not exceeding that of spontaneous earthquakes. The upper bound magnitude for RTS events observed so far is 6.3. This kind of RTS is the main concern for dam engineers.
- (3) The mechanisms of RTS are not clear but the most common perception is that the pore pressure of the reservoir water permeated into the rock reducing its effective stresses and causing the drop of shear resistance. As more commonly recognized, the effect of added weight of impounding water on the stresses is negligible in comparison with the stresses due to the weight of rock at the location of the hypocenter.
- (4) The impounding of the Zipingpu and Three Gorges reservoirs did not create any conditions to trigger the devastating Wenchuan earthquake. This earthquake also has no characteristic features of reservoir-triggered earthquakes. **IWP & DC**

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### References

- 1 Fan Xiao, 2008, *The Wenchuan Earthquake: A Fearsome Force within*, Chinese National Geography, Vol. 572, 36-52 (in Chinese)
- 2 R. A. Kerr, R. Stone, 2009, *A Human Trigger for the Great Quake of Sichuan?* Science, News of the week, 323, January: 322.
- 3 Lei Xing-lin, M Sheng-li, Wen Xue-ze 2008, *Integrated analysis of stress and regional seismicity by surface loading - A case study of Zipingpu Reservoir*, Seismology and Geology, 30(4) 1046-1063.
- 4 ICOLD Committee on Seismic Aspects of Dam Design, 2009, *Reservoirs and Seismicity - State of Knowledge*, Paris: ICOLD Bulletin 137.
- 5 Standard of Ministry of Electric Power, PRC, 2001, *Specifications for seismic design of hydraulic structures (DL 5073-2000)*, China Electric Power Press, Beijing, China,
- 6 Chen Houquin, Xu Zeping, Lee Min, 2008, *Wenchuan Earthquake and Seismic Safety of Large Dams*, Journal of Hydraulic Engineering, 39(10): 1158-1167.
- 7 Yeh Shiqiang, Qu Zhu, 1996 *Cases and Analysis of Reservoir Earthquake, Exploration, Planning and Design Institute of Water Conservation Commission of Yellow River*
- 8 Shen, H.-C., Chang, C.-H., Huang, L.-S., Li, T.-C., Yang, C.-Y., Wang, T.-C., 1974, *Earthquakes induced by reservoir impounding and their effect on Hsinfengkiang dam*, Scientia Sinica, 17(2):239-272, 1974.
- 9 Ma Zongji-jin, 2008, *Wenchuan Earthquake and Damage Evaluation*, Material for the press conference of the State Council Information Office, September 4, 2008.