RESERVOIR-TRIGGERED SEISMICITY AND EFFECT ON SEISMIC DESIGN CRITERIA FOR LARGE STORAGE DAM PROJECTS

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Abstract

Reservoir triggered seismic phenomena are seismic events which needed the incremental effects of reservoir load and the build-up of pore pressure to make them happen. The problematic association between reservoir impoundment and seismic activity has been considered in the dam engineering community since 1935, when the first documented case of reservoir-triggered seismicity (RTS) was created by impounding the Hoover arch dam in the US. In view of other similar events, interest in this phenomenon grew. Although RTS only affects a small number of dams, it has remained controversial and the subject of much study due to associated environmental impacts and risk considerations. The effect of RTS on the seismic design of large dam projects and the possible effect of RTS on buildings, infrastructure and people living in the dam and reservoir regions, is discussed. As RTS usually occurs within a few years after impounding of the reservoir, it has an effect on the seismic hazard and design criteria for appurtenant structures, buildings and infrastructure but not on the ground motion of the so-called safety evaluation earthquake, used for designing and checking the seismic safety of dams. The prediction of the largest RTS events is still not possible but by seismic monitoring, irrational concerns about dam safety can be greatly reduced. The different aspects of RTS are discussed in the paper.

Keywords: Large dam, reservoir, reservoir triggered seismicity, seismic design criteria, dam safety

1. Introduction

This paper summarizes the current state of knowledge on reservoir-triggered seismicity (RTS) from the viewpoint of dam engineers, which is documented in the ICOLD (International Commission on Large Dams) bulletin on Reservoirs and Seismicity [3]. As RTS includes different seismic safety aspects of dams, the following ICOLD bulletins [1], [2] and [4] are also very relevant for this subject. RTS is an old phenomenon. However, interest in induced seismicity caused by fracking and liquid waste storage in the US as well as geothermal projects, has grown significantly in recent years. The underlying processes of these types of seismicity are similar to that of RTS.

The first well documented case of RTS was observed in the 1930s at Lake Mead, which was created by the 220 m high Hoover arch dam in the USA. By the end of the 1960s, strong earthquakes, which are suspected of being reservoir-triggered, have occurred in the reservoirs formed by the Koyna gravity dam (India), Hsinfengkiang buttress dam (China), Kremasta embankment dam (Greece), and Kariba arch dam (Zambia), so that the general interest for this phenomenon has sharply increased. The maximum magnitudes of the seismic events observed in these reservoirs were in the range of 6.0 to 6.3. As reservoir-triggered earthquakes tend to have shallow focus, the ground motion at the dam sites of Koyna (1967) and Hsinfengkiang dams (1962) was very severe and caused structural damage to both dams. These two approximately 100 m high concrete dams were subsequently repaired and strengthened and are in operation today. The microseismic activity in the reservoir region of Koyna and Hsinfengkiang dams is still high. For example, in the Koyna dam region nearly 100 earthquakes with magnitude M>4 and about 10 events with M>5 have occurred since 1967. The ground motions caused by these earthquakes are of no serious concern for the safety of the strengthened dam.

From the very beginning, RTS was controversial and the problem remained as a target of sustained interest and studies, mainly because of its environmental impact and risk considerations. At the same time, the number of dam projects with RTS was increasing in line with the growth of the overall number of dams and the improvement in the seismic monitoring systems.

The features outlined above make RTS a concept of permanent interest for the design and monitoring of dams.

The relatively strong seismic events described above, which were mainly observed at large storage dams with maximum reservoir depth exceeding approximately 100 m and which tended to decrease with time, have been referred to as reservoir-induced seismicity in the past. ICOLD has accepted the use of the term "reservoir-triggered seismicity" as the most adequate expression as it best reflects the nature of this type of seismic events. Accordingly, the phenomena that were called reservoir-induced seismicity in the past are called reservoir-triggered seismicity today.

In order to assess the implications of RTS on the safety of large storage dam projects, it is necessary to have a proper understanding of the current seismic design criteria. Unfortunately very few who question the safety of large storage dams under the effect of RTS know about it and therefore unrealistic scenarios, questioning the safety of dams, are brought forward.

The seismic design criteria and methods of dynamic analysis of dams have undergone substantial changes since the 1930s when earthquake actions have been introduced to the design of dams. Today we have a clear concept for the seismic design criteria to be applied when a dam is subjected to ground shaking and methods of dynamic analysis have been developed, which allow the calculation of the inelastic seismic response of embankment and concrete dams.

However, we must recognize that earthquakes can cause multiple hazards in large dam projects including ground shaking, fault movements in the footprint of dams and in reservoirs, rockfalls, landslides, liquefaction, ground deformations, seepage, impulse waves in reservoirs etc. [6].

The seismic design criteria for dams, which have been updated recently by the Committee on Seismic Aspects of Dam Design of ICOLD [4] are presented. They cover the following structures and elements of large storage projects:

(i) the dam body,

(ii) the safety-relevant elements like bottom outlets and spillways (including hydro-mechanical and electro-mechanical equipment, etc.), which must be operable after a strong earthquake,

(iii) appurtenant structures including powerhouse, penstocks, desilting basins, switchyard, transmission lines, hydro-mechanical and electro-mechanical equipment etc., and

(iv) temporary structures such as cofferdams, diversion facilities, retaining structures and critical construction stages of the dam and appurtenant structures.

In the subsequent sections the different types of design earthquakes to be used for these structures and elements are discussed as well as the methods for estimating the ground motion parameters.

2. Current Seismic Design Criteria for Large Storage Dams

Only the seismic design criteria for large storage dams are discussed as RTS has mainly occurred in dam projects where the maximum reservoir depth exceeded 100 m or where the reservoir volume was over 500 Mm^3. Accordingly, the following design earthquakes are needed for the seismic design of the different structures and elements of a large dam project [4]:

- Safety Evaluation Earthquake (SEE): The SEE is the earthquake ground motion a dam must be able to resist without uncontrolled release of the reservoir. The SEE is the governing earthquake ground motion for the safety assessment and seismic design of the dam and safety-relevant components, which have to be functioning after the SEE.
- Design Basis Earthquake (DBE): The DBE with a return period of 475 years is the reference design earthquake for the appurtenant structures. The DBE ground motion parameters are estimated based on a probabilistic seismic hazard analysis (PSHA). The mean values of the ground motion parameters of the DBE can be taken. (Note: The return period of the DBE may be determined in accordance with the earthquake codes and regulations for buildings and bridges in the project region.)
- Operating Basis Earthquake (OBE): The OBE may be expected to occur during the lifetime of the dam. No damage or loss of service must happen. It has a probability of occurrence of about 50% during the service life of 100 years. The return period is taken as 145 years The OBE ground motion parameters are estimated based on a PSHA. The mean values of the ground motion parameters of the OBE can be taken.
- Construction Earthquake (CE): The CE is to be used for the design of temporary structures such as coffer dams and takes into account the service life of the temporary structure. There are different methods to calculate this design earthquake. For the temporary diversion facilities a probability of exceedance of 10% is assumed for the design life span of the diversion facilities. Alternatively the return period of the CE of the diversion facilities may be taken as that of the design flood of the river diversion

The SEE ground motion parameters can be obtained from probabilistic and/or deterministic seismic hazard analyses, i.e.

- Maximum Credible Earthquake (MCE): The MCE is the event, which produces the largest ground motion expected at the dam site on the basis of the seismic history and the seismotectonic setup in the region. It is estimated based on deterministic earthquake scenarios. According to ICOLD [4] the ground motion parameters of the MCE shall be taken as the 84 percentiles (mean plus one standard deviation).
- Maximum Design Earthquake (MDE): For large storage dams the return period of the MDE is taken as 10,000 years. For dams with small or limited damage potential shorter return periods can be specified. The MDE ground motion parameters are estimated based on a probabilistic seismic hazard analysis (PSHA). According to ICOLD [4] the mean values of the ground motion parameters of the MDE shall be taken. In the case where a single seismic source (fault) contributes mainly to the seismic hazard, uniform hazard spectra can be used for the seismic design. Otherwise, based on the deaggregation of the seismic hazard (magnitude versus focal distance) different scenario earthquakes may be defined.

For major dams the SEE ground motion parameters can be taken either as those of the MCE or MDE. Usually the most unfavorable ground motion parameters have to be taken. If it is not possible to make a realistic assessment of the MCE then the SEE shall be at least equal to the MDE.

MDE, DBE, OBE and CE ground motion parameters are usually determined by a probabilistic approach while for the MCE ground motion deterministic earthquake scenarios are used. However, for the MDE, DBE, OBE and CE also deterministic scenarios may be defined.

The different design earthquakes are characterized by the following seismic parameters:

- Peak ground acceleration (PGA) of horizontal and vertical earthquake components.
- Acceleration response spectra of horizontal and vertical earthquake components typically for 5% damping, i.e. uniform hazard spectra for CE, OBE, DBE and MDE obtained from the probabilistic seismic hazard analysis (mean values) and 84 percentile values of acceleration spectra for MCE obtained from the deterministic analysis using different attenuation models.
- Spectrum-compatible acceleration time histories for the horizontal and vertical components of the MCE ground motion determined either from a random process or by scaling of recorded earthquake ground motions. The artificially generated acceleration time histories of the horizontal and vertical earthquake components shall be stochastically independent. To account for aftershocks, it is recommended to increase the duration of strong ground shaking.

In case of fault movements, similar estimates are required as for the ground shaking. It appears that it is quite difficult for the dam designer to get quantitative estimates of fault movement parameters for the different types of design earthquakes.

For underground structures where the effects of imposed deformations are more relevant than inertial effects, the displacement parameters of the ground motion are also needed.

The best description of the ground motion is by means of the acceleration time histories. They are needed for any nonlinear dynamic analysis of dams and components. It is also expected that inelastic deformations take place under the SEE ground motion. According to ICOLD [4] the following aspects of the ‘design acceleration time history’ should be considered:

(1) The three components of the spectrum-matched acceleration time histories must be statistically independent.

(2) The acceleration time histories of the horizontal earthquake components may be assumed to act in along river and across river directions. No modifications in the horizontal earthquake components are needed if they are applied to other directions.

(3) The duration of strong ground shaking shall be selected in such a way that aftershocks are also covered.

(4) In the case of dams, which are susceptible to damage processes which are governed by the duration of strong ground shaking such as, e.g., the build-up of pore pressures, earthquake records with long duration of strong ground shaking shall be used.

(5) The spectrum-matched acceleration time histories with extended duration of strong ground shaking used for the seismic analysis and design of the dams may be quite different from real ones; however, their use will lead to a safe design.

(6) For the safety check of a dam at least three different earthquakes shall be considered for the SEE ground motion.

It must be added that for the seismic design of dams ground motion parameters are used, which do not have the characteristics, the earth scientists feel are physically correct, i.e. duration of strong ground shaking, near field and directivity effects, spectrum shape of main shocks and aftershocks etc. However, the dam designer will use simplified models of the design earthquake ground motion (so-called load model) and methods of dynamic analysis that lead to a safe design, even if the earthquake load models do not comply with the real nature of the earthquake ground motion! This concept may be difficult to accept by seismologists and other experts, who are not familiar with the seismic design of dams. However, the use of load models for live loads etc., which do not represent reality, is standard practice in the design of buildings, bridges and other structures. The same is true for the seismic design of dams.

3. Effects of RTS on Dam Safety

Today it is generally accepted that significant reservoir-triggered earthquakes can only occur in regions with high tectonic stresses in the earth crust, i.e. the causative fault that can produce the earthquake is already in near failure conditions, so that added gravity stresses and pore pressure propagation due to reservoir impounding, can trigger the seismic energy release. This means that triggering due to impounding cannot change the underlying tectonic processes and the long-term seismic hazard at the dam site, if the seismic potential at a dam site is correctly assessed.

The basic requirements for reservoir-triggered seismic activity are [3]:

- the existence of active faults in the reservoir region, or
- the existence of faults near failure limit (i.e. high tectonic stresses in reservoir region).

A large dam, which has been designed against earthquakes according to the current state of practice requiring that the dam can safely withstand the ground motions caused by the SEE, can also withstand the effects of the largest reservoir-triggered earthquake as the SEE ground motions are, per definition, larger than those caused by the strongest RTS events. Therefore, there is no need to consider an extra RTS load case in the design of dams.

As the magnitudes of reservoir-triggered earthquakes is decreasing with time, it is rather unlikely that such events will jeopardize the safety of existing dams, even if they were not designed according to the current state of practice. However, it is strongly recommended that the earthquake safety of dams, which have a continuing record of increased seismicity, be re-assessed, especially when they have been designed against earthquakes using design criteria and methods of dynamic analysis, which are considered as outdated or even obsolete today, such as the pseudo-static seismic design method with a seismic coefficient of 0.1, which has been common practice in the past.

It is understood, based on the observation of dams during strong earthquakes, that well designed and constructed dams can withstand ground motions of near-field earthquakes with magnitudes of 5 or larger and remain functional, i.e. are undamaged.

The Koyna gravity dam and Hsinfengkiang buttress dam mentioned earlier, which were damaged during earthquakes, had unusual shapes that were vulnerable to earthquake shaking. Moreover they had been designed against earthquakes using the pseudo-static analysis method with a seismic coefficient, which was unrelated to the seismic hazard at the dam site. In other words, these dams were not designed according to the current seismic design practice for large dams as presented in the previous section.

4. Effects of RTS on Existing Buildings and Infrastructure in Reservoir Region

Relatively strong reservoir-triggered earthquakes may cause damage to existing buildings and structures in the project region. During the magnitude 6.3 Koyna earthquake of 1967 about 100 people were killed in villages in the dam region. The damaged (mainly non-engineered) buildings were not designed for earthquakes as the region of the dam was not considered as a seismic area at the time the dam was constructed. Although the earthquake has occurred in the reservoir region, it is questioned if this earthquake has actually been triggered by the reservoir or if it would have occurred anyway sometimes in the future. Therefore, dam owners would object to the classification of strong earthquakes in the reservoir region of large storage dams as being triggered by the reservoir.

A reservoir-triggered earthquake with a magnitude of 6.3 (observed maximum magnitude for reservoir-triggered earthquake) can cause peak ground accelerations that may approach those caused by the SEE. However, the duration of strong ground shaking of RTS events is usually much smaller than that of the SEE. It has to be kept in mind that the duration of strong ground shaking is responsible for a major part of the earthquake damage to structures and not the peak ground acceleration, especially when there is a single, high-frequency peak of the ground acceleration. Nevertheless, reservoir-triggered earthquakes can still cause considerable damage to buildings and structures, which have not been designed for earthquake actions.

The main difference between a reservoir-triggered earthquake and a natural earthquake is that the reservoir-triggered earthquake has a relatively high likelihood of occurring within the first few years after impounding of the reservoir or when the reservoir level has reached its maximum elevation. These earthquakes have often a shallow focus and their epicenters are relatively close to the dam sites. Thus the short-term seismic hazard for moderate earthquakes may increase. However, prediction of the size, date and place of major RTS events is still not possible.

5. Effects of RTS on the Seismic Design of Dams, Appurtenant Structures, Buildings and Infrastructure in Reservoir Region

If RTS is possible then the DBE and OBE ground motion parameters, discussed in Section 2, should cover those from the critical and most likely RTS scenarios as such events are like to occur within years after the start of the impounding of the reservoir. This means that the DBE and OBE ground motion parameters must be increased if they are lower than those estimated for the largest RTS events. But as mentioned earlier, the RTS ground motion parameters are lesser than those of the SEE.

As prediction of the strongest RTS events is still not possible, therefore the following solutions may be considered by the dam owner to minimize the risk of claims from damage caused by unpredictable RTS events:

(i) conservative seismic design of appurtenant structures and all new structures in the reservoir region, i.e. by assigning higher importance and lower “ductility” factors if seismic design codes or standards for buildings are used;

(ii) to wait with the construction of new structures in reservoir region until RTS has diminished; and

(iii) to establish a database of all buildings and structures in the project area, which could be damaged by RTS and to use this as a basis for the assessment of claims if RTS is observed.

Other solutions are also possible. However, to abandon a dam project because of anticipated RTS as put forward by dam opponents would be a wrong solution as up to now no dam project, known to the author, has been abandoned because of RTS and there are many other hazards from the natural and man-made environment as well as site-specific and project-specific hazards, which have more severe implications on the safety of projects than RTS. Therefore, this would be an unbalanced over-reaction and would lack objectivity.

Irrespective of these solutions, monitoring of the seismicity in the reservoir region as discussed in the subsequent section is strongly recommended.

6. RTS Monitoring

For settling any reservoir-triggered earthquake claims a comprehensive monitoring of the seismicity before dam construction and during and after impounding of the reservoir is required in order to dispel any doubts about what is actually happening. The monitoring system should be capable to record the microseismic activity in the reservoir region and to record the strongest events, which can cause damage (mainly cracks and deformations) in buildings. The regional seismic networks may not be enough as the density of networks in the often remote areas, where dams are located, is inadequate. However, microseismic monitoring is necessary for new dam projects where many people are living in the reservoir area and/or where important industries and infrastructures are located.

A project-specific network may include at least 4 to 6 seismic stations. These can be either geophones or sensitive accelerometers. Accelerometers are also used for the strong motion monitoring of dams, gated spillways and appurtenant structures, but this monitoring system is different from that of RTS monitoring.

Based on the results of the RTS monitoring system different features of RTS can be found as discussed in the case studies presented in reference [3]. There are cases, e.g., in seismically active regions, where the identification of RTS may be rather difficult and long-term monitoring with a sophisticated monitoring system will be required.

As large dam construction has peaked off in many countries, it is unlikely that the number of new dam projects, which will experience RTS, is growing substantially in the coming years. The dams where RTS was observed and is still taking place are not considered as a major risk as the seismicity and the maximum magnitudes of the shocks tend to decrease with time. However, it is strongly recommended to monitor continuously the ongoing seismicity in the reservoir region where RTS has been observed in the past and to install monitoring systems in the reservoir region of future dams where reservoir-triggered seismicity is expected. Monitoring must start well ahead of time, to properly record the natural seismicity in the project area, which will then be used as a benchmark. If instruments are placed too late it is very likely that the observed activity will be attributed to the reservoir and its owner.

7. Effect of RTS on Landslide and Rockfall Hazard

The main dam safety concern of RTS is the landslide and rockfall hazard as mass movements into the reservoir can cause impulse waves and overtopping of the dam or they may block intakes or damage gates or motors for operating spillway gates. Such mass movements can already be triggered by smaller earthquakes (i.e. smaller than the SEE). Of main concern are mass movements close to the dam, intake structures and spillways. Based on the damage caused by landslides to hydropower projects in the epicentral region of the May 12, 2008 Wenchuan earthquake in China, it is concluded that the landslide and rockfall hazards have been underestimated and not addressed in the dam design in equal detail than the effect of ground shaking.

In Fig. 1 landslides are shown, which occurred near the 152 m high Zipingpu concrete face rockfill dam during the Wenchuan earthquake. These mass movements were not dangerous as they are shallow slides that occurred when the reservoir was only 30% full, i.e. impulse waves had no effect on the dam as the freeboard was very large. The ground motions at the dam site corresponded roughly to those of the SEE for this project.

Fig. 1. Rockfalls in the Zipingpu reservoir area caused by the May 12, 2008 Wenchuan earthquake in China (photo taken from Zipingpu dam crest when reservoir was full, April 2009)

The triggering of landslides in mountainous regions by earthquakes depends also on the weather conditions. For example, the author was in Muzaffarabad in Kashmir, Pakistan on October 26, 2015 when a magnitude 7.5 earthquake occurred in neighboring Afghanistan wit epicentral distance of approx. 350 km and focal depth of 210 km. This earthquake could be felt very well and caused the opening of the top joint at the connection of the infill wall with the reinforced concrete structure in the meeting room he was staying. No roads were blocked by mass movements on the way to Muzaffarabad.

On April 10, 2016 another earthquake with magnitude 6.6 occurred in the same region with a focal depth of 210 km. By coincidence the author visited Muzaffarabad a week after this smaller earthquake and was informed that a number of mass movements were caused by this distant earthquake, which blocked roads around Muzaffarabad. One of the major slides involved 80 buildings as shown in Fig. 2.

Although the ground motions of the magnitude 6.6 earthquake were lesser than those of the magnitude 7.5 event in the previous year, mass movements were mainly caused by the smaller earthquake as prior to that earthquake it was raining. The combination of saturated slopes with ground shaking triggered several slides. The same could happen during RTS if the reservoir rim is prone to landslides and if this hazard has not been addressed properly. If such a massive landslide should be triggered in the reservoir region by RTS, this could be a major problem for a dam owner, as due to unfavorable circumstances mass movements could be triggered by minor seismic events.

Fig. 2. Major landslide in Kashmir, Pakistan, triggered by magnitude 6.6 earthquake of April 10, 2016 in Afghanistan (epicentral distance: approx. 350 km, focal depth: approx. 210 km)

As a matter of fact, slopes, where landslides could block safety-relevant elements, have to be checked for the SEE as well. If the safety has been confirmed then RTS is not a problem.

The same applies to mass movements, which can cause major impulse waves in the reservoir. These slopes must also be checked for the SEE. If the freeboard is adequate then RTS is not a problem.

It must be pointed out that mass movements occur primarily in mountainous regions where the (sliding) stability of natural slopes is close to 1. The main problem with slope stability is that this is mainly done by geologists who are not familiar with the seismic design criteria for large dams and that some of these seismic criteria apply also to the safety of the reservoir slopes.

8. Psychological and other Effects of RTS

As pointed out in the previous sections, RTS is not a safety problem for a well-designed and constructed dam or the people who could be at risk in the case of a dam failure; however, if unexpected seismic events occur more frequently, people living below a dam may start questioning its seismic safety. To dispel such safety concerns may not be that straightforward, because acceptance of scientific and technical arguments is often still limited among the people living in the project area.

Microseismic activity can also cause disturbing noise. This may create safety concerns and promote irrational and superstitious beliefs especially when such noise is persisting.

Continuous monitoring of the seismic activity in the reservoir region before, during and after reservoir impounding is probably one of the best ways to respond to psychological concerns of any parties involved in a dam project.

In most cases RTS has manifested by ground shaking and/or noise. The magnitudes of RTS events are generally small and do not cause any damage [5]. RTS has been observed in over 100 reservoirs. In the case of the 185 m high Katse arch dam in Lesotho RTS events occurred during impounding of the reservoir and movements on shears were observed in an upstream village, which were not related to active faults but to high stresses in the basalt layer overlaying old sandstone formations. The largest event had a magnitude of 3.0. The fissures opening along a shear zone caused some damage to seismically weak local buildings (stone-mud structures) and the depletion of wells. The damage had to be compensated by the dam owner.

9. Wenchuan Earthquake of May 12, 2008

Prior to the May 12, 2008 Wenchuan earthquake in China only a few large dams had been exposed to very strong ground shaking and suffered different degrees of damage, but none of them had failed. During this magnitude 7.9 earthquake 1803 dams and reservoirs and 403 hydropower plants with an installed capacity of 3.3 GW were damaged. The main damage was in Sichuan province but other provinces have also been affected [6].

Shortly after the Wenchuan earthquake reports have appeared, which suggested that this devastating earthquake was triggered by the impounding and operation of the Zipingpu reservoir. The main arguments for this suggestion were, firstly, the observation that large reservoirs can trigger earthquakes, secondly, that the epicentre of the Wenchuan earthquake is located 17 km from the Zipingpu dam and, thirdly, a small part of one branch of the reservoir intersects the fault, which ruptured during the earthquake.

From March 29 to April 4, 2009 a joint mission of ICOLD and the Chinese National Committee on Large Dams was arranged by the author. Thirteen foreign dam and earthquake experts and an equal number of Chinese experts participated in this mission. A position paper on reservoirs and the Wenchuan earthquake was prepared, in which the issue of triggering of the Wenchuan earthquake by the Zipingpu reservoir was addressed. Some of the important statements are given below [6]:

"The maximum water level of the Zipingpu reservoir (elevation 875.4 m asl) has not exceeded the natural water level (elevation 877 m asl) where the Min River is crossing the Beichuan-Yinxiu fault. Therefore, the original

hydrogeological conditions of the Beichuan-Yinxiu fault have not been affected by the impounding of the Zipingpu reservoir.

In August 2004, 13 months before reservoir impounding, an earthquake monitoring network with seven fixed stations was set up in the reservoir region. In October 2006, the reservoir water level reached elevation 875.4 m asl, 1.6 m below normal storage level. The corresponding reservoir volume was 900 Mm^3. In July 2006 and May 2007, the water level was lowered to elevation 820 m asl. Before the Wenchuan earthquake (April 30, 2008), the reservoir water level was at elevation 828.95 m asl, the corresponding reservoir volume was 300 Mm^3. 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 almost unchanged before and after reservoir impounding (Fig. 3). *The recorded seismicity has also no relation with the reservoir water level variation."*

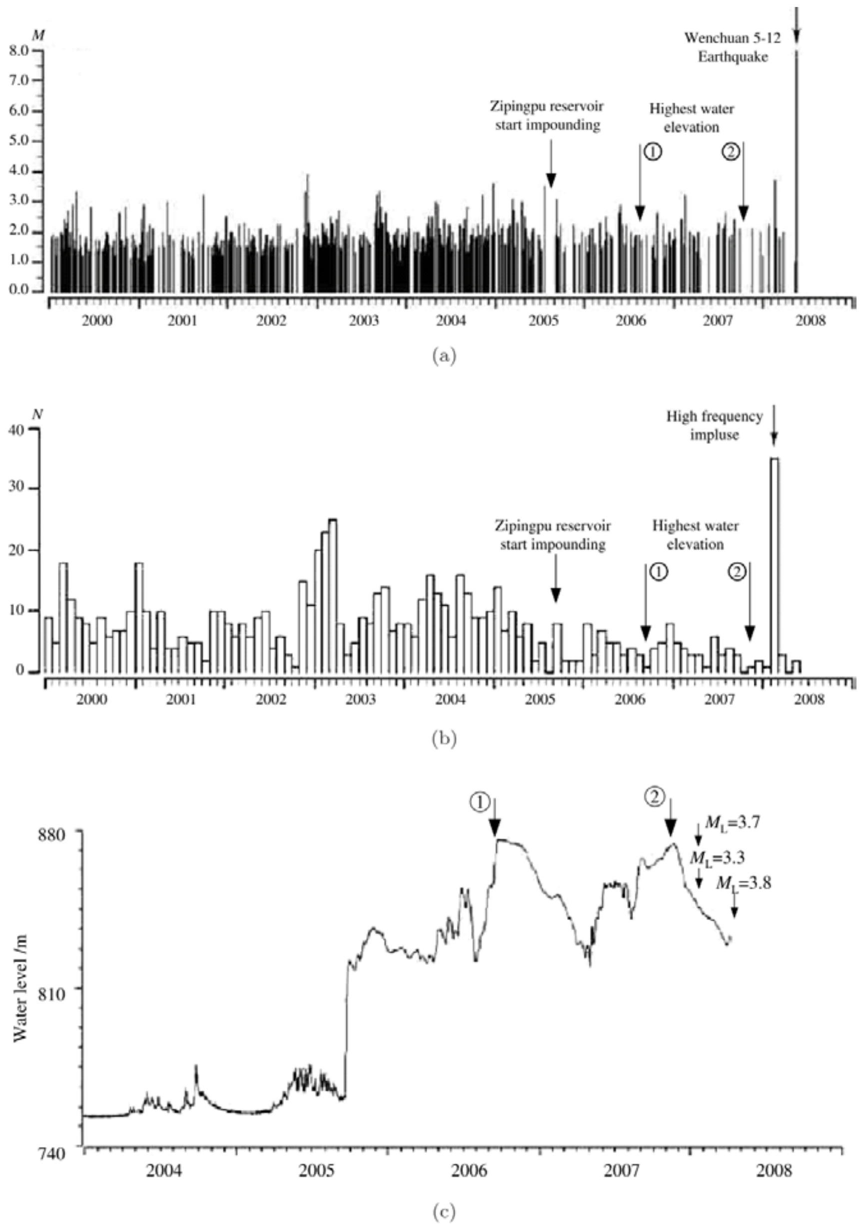

Fig. 3. Distribution of magnitude and frequency in the region of Zipingpu reservoir. (a) Magnitude distribution ($M_L \geq 1.0$), (b) frequency distribution ($M_L \geq 1.0$), and (c) reservoir level fluctuation [7].

Moreover, as the Wenchuan earthquake has no features of "typical" RTS events the main conclusion of the expert panel was that there is no factual evidence that the Wenchuan earthquake was triggered by the impounding of the Zipingpu reservoir. This statement is still valid today. The dam engineers are convinced that the Wenchuan is not a reservoir-triggered earthquake, but earth scientists still make contradictory statements without giving supporting evidence [6], [7] and [8].

This example shows that the definition of RTS is not straightforward when an assessment of the triggering mechanisms of the strongest events near dams and reservoirs has to be made and justified by evidence. Moreover, if a tectonic fault is close to failure then it is almost impossible to determine the exact factors triggering a major earthquake. This is also the case for the Wenchuan earthquake.

10. Conclusions

In the seismic safety assessment of dams it is not necessary to treat RTS as a separate load case as the ground motion caused by the safety evaluation earthquake (SEE) is more severe than that of the largest reservoir-triggered earthquake.

The maximum observed magnitude for reservoir-triggered earthquakes is about 6.3. It is almost impossible to prove that the occurrence of a strong earthquake has been caused or influenced by the impounding of a reservoir as the focal depth is usually several kilometers and it is not possible to measure the in situ stress field and the strength properties along faults.

Reservoir-triggered earthquakes may cause mass movements (landslides, rockfalls, avalanches, debris flows etc.) into the reservoir, resulting in water waves that could cause overtopping of a dam. An adequate freeboard has to be provided during the period of increased mass movement hazard.

Natural slopes in the reservoir region, which are prone to failure, may fail even under small ground movements. Such slopes are a problem if the can cause damage to buildings and infrastructure (mainly roads in mountainous regions).

Buildings and structures in the reservoir region are normally designed according to seismic building codes. If the ground motion parameters of the design basis earthquake (DBE) for buildings and other structures in the reservoir area are lesser than those of the strongest RTS event, then the DBE ground motion parameters shall be increased to cover RTS events, which are likely to occur within a short period after impounding of the reservoir. The same adjustment will be needed for the ground motion parameters of the operating basis earthquake used for the design of the dam and safety-relevant elements. However, the safety of the dam and safety-relevant elements (spillways and bottom outlets) must be checked for the SEE, which is much more severe than the OBE.

Reservoir-triggered microseismic activity, which can be felt or heard, creates safety concerns among the people living below dams, which have to be taken up seriously by the dam owners.

Monitoring of the seismic activity prior, during and after impounding of a reservoir is highly recommended for large storage dams and dams located in tectonically stressed regions.

If a tectonic fault is close to failure then it is almost impossible to determine the exact factors triggering a major earthquake. The same applies to the largest events, which are assumed to have been triggered by the impounding of reservoirs..

The magnitude 7.9 Wenchuan earthquake in China does not have features of RTS and there is no evidence for any claim that it was triggered by the impounding of the Zipingpu reservoir.

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