Dam safety and earthquakes

IWP&DC presents a position paper of the International Commission on Large Dams (ICOLD), prepared by the Committee on Seismic Aspects of Dam Design

UNTIL now no people have died from the failure or damage of a large water storage dam due to earthquake. Earthquakes have always been a significant aspect of the design and safety of dams.

A large storage dam consists of a concrete or fill dam with a height exceeding 15m, a grout curtain or cut-off to minimise leakage of water through the dam foundation, a spillway for the safe release of floods, a bottom outlet for lowering the reservoir in emergencies, and a water intake structure to take the water from the reservoir for commercial use. Depending on the use of the reservoir there are other components such as a power intake, penstock, powerhouse, device for control of environmental flow, fish ladder, etc.

During the Richter magnitude 8 Wenchuan earthquake of 12 May 2008, 1803 concrete and embankment dams and reservoirs and 403 hydropower plants were damaged. Likewise, during the 27 February 2010 Maule earthquake in Chile of Richter magnitude 8.8, several dams were damaged. However, no large dams failed due to either of these two very large earthquakes.

What earthquake action does a dam have to withstand?

In order to prevent the uncontrolled rapid release of water from the reservoir of a storage dam during a strong earthquake, the dam must be able to withstand the strong ground shaking from even an extreme earthquake, which is referred to as the Safety Evaluation Earthquake (SEE) or the Maximum Credible Earthquake (MCE). Large storage dams are generally considered safe if they can survive an event with a return period of 10,000 years, i.e. having a one percent chance of being exceeded in 100 years. It is very difficult to predict what can happen during such a rare event as very few earthquakes of this size have actually affected dams. Therefore it is important to refer to the few such observations that are available. The main lessons learnt from the large Wenchuan and Chile earthquakes will have an impact on the seismic safety assessment of existing dams and the design of new dams in the future.

There is a basic difference between the load bearing behaviour of buildings and bridges on the one side, and dams. Under normal conditions buildings and bridges have to carry mainly vertical loads due to the dead load of the structures and some secondary live loads. In the case of dams the main load is the water load, which in the case of concrete dams with a vertical upstream face acts in the horizontal direction. In the case of embankment dams the water load acts normal to the impervious core or the upstream facing. Earthquake damage of buildings and bridges is mainly due to the horizontal earthquake component. Concrete and embankment dams are much better suited to carry horizontal loads than buildings and bridges. Large dams are required to be able to withstand an earthquake with a return period of about 10,000 years, whereas buildings and bridges are usually designed for an earthquake with a return period of 475 years. This is the typical building code requirement, which means the event has a 10% chance of being exceeded in 50 years. Depending on the risk category of buildings and bridges, importance factors are specified in earthquake codes, which translate into longer return periods, but they do not reach those used for large dams.

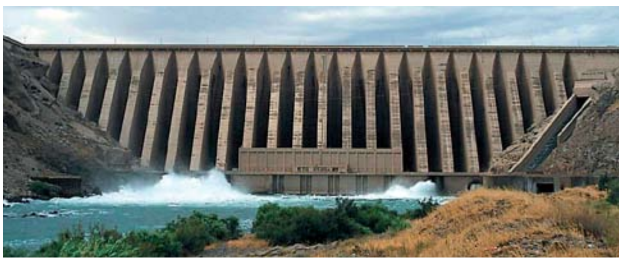
Moreover, most of the existing buildings and bridges have not been designed against earthquakes using modern concepts, whereas dams have been designed to resist against earthquakes since the 1930s. Although the design criteria and analyses concepts used in the design of dams built before the 1990s are considered as obsolete today, the reassessment of the earthquake safety of conservatively designed dams shows that in general these dams comply with today's design and performance criteria and are safe. In many parts of the world the earthquake safety of existing dams is reassessed based on recommendations and guidelines documented in bulletins of the International Commission on Large Dams (ICOLD).

Seismic hazard is a multi-hazard

Earthquakes represent multiple hazards with the following features in the case of a storage dam:

Ground shaking causes vibrations and structural distortions in dams, appurtenant structures and equipment, and their foundations;

Fault movements in the dam foundation or discontinuities in dam foundation near major faults can be activated, causing structural distortions;



Left: Maigrauge gravity dam built in 1872 in Switzerland. After a recent rehabilitation its service life has been extended by another 50 years. Photo shows the main elements of a storage dam for power production: spillway, reservoir, concrete dam body, power intake and powerhouse (left) ; Below from left to right: Downstream view of the 106 m high Sefid Rud buttress dam in Iran damaged by the magnitude 7.5 Manjil earthquake of June 21, 1990. Bottom irrigation outlets were opened after the earthquake to lower the reservoir (left). Rockfall damage near left abutment (middle) and right abutment (right).

Above left to right: Different types of damage of embankment dams caused by the magnitude 7.5 Bhuj earthquake in Gujarat province, India, January 26, 2001. Mainly small dams for irrigation and water supply were damaged. Right: Damage of reinforced concrete buildings on top of intake towers of the Zipingpu reservoir, May 12, 2008 Wenchuan earthquake

- Fault displacement in the reservoir bottom may cause water waves in the reservoir or loss of freeboard;
- Rockfalls and landslides may cause damage to gates, spillway piers (cracks), retaining walls (overturning), surface powerhouses (cracking and puncturing and distortions), electro-mechanical equipment, penstocks, masts of transmission lines, etc.
- Mass movements into the reservoir may cause impulse waves in the reservoir;
- Mass movements blocking rivers and forming landslide dams and lakes whose failure may lead to overtopping of run-of-river power plants or the inundation of powerhouses with equipment, and damage downstream;
- Ground movements and settlements due to liquefaction, densification of soil and rockfill, causing distortions in dams; and
- Abutment movements causing sliding of and distortions in the dam.

Effects such as water waves and reservoir oscillations (seiches) are of lesser importance for the earthquake safety of a dam. Usually the main hazard, which is addressed in codes and regulations, is the earthquake ground shaking. It causes stresses, deformations, cracking, sliding, overturning, etc. However, some of the other hazards, which are normally not covered by codes and regulations, are also important.

Therefore, in the earthquake design of dams all seismic hazard aspects must be considered and depend on the local conditions of a storage dam project.

What could happen in strong earthquakes?

The experience with the seismic behaviour of large dams is still limited. Four dams – two concrete, an earth core rockfill and a concrete face rockfill dam – with heights exceeding 100m were damaged during the Wenchuan earthquake. Elsewhere, there are another five concrete dams over 100m in height, which were damaged due to strong ground shaking. In concrete dams the damage was mainly in the form of cracks but also joints can open up leading to the release of water from the reservoir. In modern embankment dams the damage is mainly by deformations and cracks along the crest that can eventually lead to internal erosion and piping through the dam.

However, we have to be aware that each dam is a prototype located at a site with special site conditions and hazards. Therefore, based on the observation of the earthquake behaviour of other dams it is still very difficult to make a prediction of the damage that could occur in a particular dam. At this time we are still in a learning phase as very few large modern dams have been exposed to strong earthquakes. In the case of the Wenchuan earthquake, a large number of rockfalls took place, which caused significant damage to dams and appurtenant structures. Surface powerhouses were particularly vulnerable to rockfalls in the steep valleys in the epicentral region of the Wenchuan earthquake.

Could reservoirs be lowered in case of successful earthquake predictions?

If earthquakes could be predicted, one could attempt to lower the reservoir prior to the occurrence of a large earthquake. There are two problem areas related to this concept. First, despite some 40 years of research on earthquake prediction, it is still not possible to predict the time, location and size of a large earthquake reliably. Small earthquakes may be predicted but not large ones. The prediction is usually given in terms of the probability of occurrence, e.g. there is a 50% probability that a magnitude 7 earthquake occurs in a certain region within a period of 30 years. Such predictions are basically useless for warning purposes and for lowering a reservoir.

Even if a large earthquake could be predicted reliably, there would not be sufficient time to lower large reservoirs. Lowering of a reservoir would have to happen by low level outlets (bottom outlets) or the power waterways if the intake is at low elevation. Unfortunately, bottom outlets are not available everywhere. Therefore the lowering of a reservoir by say 50% may take weeks or months, and in some cases it may not be possible at all.

As a conclusion, earthquake prediction, which is a slowly developing science, is not a viable option to improve the earthquake safety of dams. The only real option is to have a dam which can withstand the strongest earthquake effects to be expected at the dam site. This is the current practice in dam design.

The greatest hazard of a dam is the water in the reservoir. Therefore, in the seismic design of dams, we have to ensure the safety of the dam under full reservoir condition. Although an arch dam may be more vulnerable to the effect of ground shaking when the reservoir

Above left: Damage of the Shapei powerhouse caused by rockfall during the May 12, 2008 Wenchuan earthquake; Above right: Sheared off pier of Futan weir at the Minjiang river due to the impact of large rocks, May 12, 2008 Wenchuan earthquake

is empty, this case is not critical for the safety of the people living downstream of the dam but it is, of course, an important economical issue for the dam owner if the dam should fail.

Can earthquakes be triggered by storage dams?

There are a number of cases where earthquakes were triggered by the reservoir. The main prerequisites for reservoir-triggered seismicity (RTS) are (i) the presence of an active fault in the reservoir region, or (ii) existence of faults with high tectonic stresses close to failure. The filling of the reservoir in a tectonically active region may merely cause the triggering of an earthquake which in any case would occur at a later date. The occurrence of RTS has been mainly observed in reservoirs with a depth exceeding 100m. Six events with Richter magnitudes of more than 5.7 have been observed up to now. The largest magnitude was 6.3. In two cases, concrete dams were damaged, i.e. Hsinfengkiang buttress dam in China and Koyna gravity dam in India. Since records did not exist on the local seismicity prior to dam construction, there are still doubts whether these large earthquakes have actually been triggered by the reservoirs.

If a large dam has been designed according to the current state-of-practice, which requires that the dam can safely withstand the ground motions caused by an extreme earthquake, it can also withstand the effects of the largest reservoir-triggered earthquake. However, RTS may still be a problem for the buildings and structures in the vicinity of the dam, because they would generally have a much lower earthquake resistance than the dam. In the great majority of RTS, the magnitudes are small and of no structural concern.

The issue of RTS is always discussed in connection with large dams. RTS was also considered in connection with the Wenchuan earthquake as the Zipingpu reservoir is located close to the ruptured segment of the Longmenshan fault. However, there is no conclusive evidence that the earthquake was triggered by the filling and the operation of the reservoir.

What are the main concerns with respect to the earthquake safety of large storage dams?

The main concerns are related to the existing dams, which either have not been designed against earthquakes – this applies mainly to small and old dams – and dams built using design criteria and methods of analyses which are considered as outdated today. Therefore, it is not clear if these dams satisfy today's seismic safety criteria. There is a need that the seismic safety of existing dams be checked and modern methods of seismic hazard assessment be used such as the guidelines given in ICOLD Bulletin 120. This will result in a dam which will perform well during a strong earthquake. To follow these guidelines is more important than to perform any sophisticated dynamic analysis, which is only a tool to help understand how a dam will perform.

The role of ICOLD

Hoover Dam in the US built in the 1930s was the first concrete dam designed against earthquake where both the inertial effects of the dam and the hydrodynamic pressure of the reservoir were taken into account. Embankment dams were designed against earthquakes as early as in the 1920s in Japan where the seismic action was taken into account in the stability analyses.

ICOLD has discussed the effects of earthquakes on dams at several Congresses and Annual Meetings. At the 5th ICOLD Congress in Paris, France in 1955 the following subject was discussed: 'Settlement of earth dams due to compressibility of the dam materials or of the foundation, effect of earthquakes on the design of dams'.

In June 1968 the ICOLD Committee on Earthquakes was established. This committee now exists under the name: Committee on Seismic Aspects of Dam Design. Thirty-one countries from all continents are represented in this important committee. In recent years the following Bulletins have been published by the committee:

- Bulletin 62 (1988 revised 2008): Inspection of dams following earthquakes – guidelines;
- Bulletin 72 (1989 revised 2010): Selecting seismic parameters for large dams - guidelines;
- Bulletin 112 (1998): Neotectonics and dams - guidelines;
- Bulletin 113 (1999): Seismic observation of dams - guidelines;
- Bulletin 120 (2001): Design features of dams to effectively resist seismic ground motion - guidelines;
- Bulletin 123 (2002): Earthquake design and evaluation of structures appurtenant to dams - guidelines; and
- Bulletin 137 (2010): Reservoirs and seismicity – state of knowledge.

Conclusions

The technology is available for building dams and appurtenant structures that can safely resist the effects of strong ground shaking.

Storage dams that have been designed properly to resist static loads prove to also have significant inherent resistance to earthquake action. Many small storage dams have suffered damage during strong earthquakes. However, no large dams have failed due to earthquake shaking.

Earthquakes create multiple hazards at a dam that all need to be accounted for. There are still uncertainties about the behaviour of dams under very strong ground shaking, and every effort should be made to collect, analyze and interpret field observations of dam performance during earthquakes. IWP&DC

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