Seismic safety evaluation of existing dams

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ABSTRACT:

Since the 1930s, when the pseudo-static analysis methods were introduced for the seismic design of concrete and embankment dams, the following major developments have taken place: (i) change from pseudo-static to dynamic seismic analysis of dams, (ii) change from the representation of the earthquake ground shaking by a seismic coefficient to safety evaluation earthquake ground motion parameters, (iii) change from single ground shaking hazard to multiple seismic hazards including mass movements, and faulting, and (iv) change from safety factor and allowable stress concepts to rational seismic performance criteria, characterized mainly by dam deformations. There are still considerable uncertainties about the behavior of dams under strong ground shaking. For the seismic safety assessment of dams stress and deformation analyses and dynamic stability analyses are usually required. The bases of any numerical analysis are seismic design and safety criteria. Today, according to ICOLD Bulletin 148 "Selecting Seismic Parameters for Large Dams" two levels of earthquake ground motion are specified for new dams, i.e. the operating basis earthquake (OBE) and safety evaluation earthquake (SEE) ground motions. For existing dams the safety check may only be required for the SEE. The seismic design criteria, the seismic load combinations and the seismic performance and safety criteria of new and existing dams are discussed and recommendations are made for the seismic safety evaluation of existing dams, which were designed using outdated seismic design criteria and methods of seismic analysis.

1 INTRODUCTION

The milestone in the seismic analysis of dams was the 1971 San Fernando earthquake in California where damage was caused to embankment dams (San Fernando dams) and also to an arch-gravity dam (Pacoima dam). Following this event a few dams were analyzed using modern methods of dynamic analysis, mainly linear-elastic analyses. Until 1989, when ICOLD published Bulletin 72 "Selecting Seismic Parameters for Large Dams", most dams designed against earthquakes used the pseudo-static analysis method with the ground motion represented by a seismic coefficient of typically 0.1 almost irrespective of the seismic hazard at the dam site. Today's minimum seismic design criteria are those given in ICOLD Bulletin 148, a revision of Bulletin 72. The basic seismic safety concept is that a dam with a large damage potential must be able to resist the strongest ground motion to be expected at the dam site.

Several strong earthquakes have caused damage to water storage dams, some of the important events are listed below:

(i) During the 1990 Manjil earthquake in Iran, the 106 m high Sefid Rud buttress dam was subjected to a ground motion that could be expected during the maximum credible earthquake (MCE).

(ii) A concrete weir was severely damaged by fault movements and ground shaking during the September 21, 1999 Chi-Chi earthquake in Taiwan.

(iii) About 245 dams for water supply and irrigation were damaged by the Bhuj earthquake of January 26, 2001 in Gujarat, India as a result of liquefaction. Almost all of them were small earth dams and had to be strengthened after the earthquake.

(iv) During the May 12, 2008 Wenchuan earthquake in Sichuan, China, 1803 dams and reservoirs and 403 hydropower plants with an installed capacity of 3.3 GW were damaged. The great majority of the dams were small earth embankments, but several large dams were also affected. Among the large damaged dams was the Zipingpu concrete-face rockfill dam with a height of 156 m.

(v) Until March 11, 2011 nobody died from the failure or damage of a large water storage dam due to an earthquake. However, during the magnitude 9.0 Tohoku earthquake in Japan in 2011 an 18.5 m high embankment dam failed and the flood wave created by the release of the reservoir caused the loss of eight lives.

There were other strong earthquakes that caused damage to water storage dams in Chile, Japan, the Philippines, and the USA. Furthermore, a few tailings dams failed during strong earthquakes in Chile and caused loss of lives.

If designed against earthquakes, the damaged dams were designed for earthquakes using the pseudo-static analysis method. Accordingly, if the allowable factors of safety against sliding and the stresses were within the allowable stress limits in concrete dams, these dams should have been undamaged during strong earthquakes. But this was not the case; therefore the following conclusions may be drawn:

- Dams are not inherently safe against earthquakes. To date, only an 18.5 m high embankment dam failed during the 2011 Tohoku earthquake in Japan, where eight people lost their lives in a flood wave caused by dam failure. Because of the satisfactory behavior of dams during earthquakes, several engineers and owners may be of the opinion that a dam, which has survived for say over 50 years without any earthquake damage, is safe against earthquakes. This is a misconception, especially in areas of low to moderate earthquakes, where strong earthquakes occur rarely.
- The pseudo-static analysis and design method are not safe. That the pseudo-static method, which does not account for the dynamic properties of dams and the seismic coefficient used is an inadequate parameter for characterizing the earthquake ground motion. That the pseudo-static analysis method is not suitable for large dams was already known since the February 9, 1971 San Fernando earthquake in the USA, i.e. 50 years ago. Although the pseudo-static method is outdated or even wrong, when used for the safety evaluation of large storage dams subjected to the ground motions of the so-called Safety Evaluation earthquake (SEE), it is still used today.
- All dams, both new and existing ones, must satisfy the present seismic design and safety criteria, which are different from those used during the design of most existing dams built before the 1980s. Therefore, the actual seismic safety of these dams is not known, and therefore, the seismic safety of the existing dams should be checked. This has been a major concern of the ICOLD Committee on seismic Aspects of Dam Design since 1999, when the author became chairman of this committee.

Much know-how exists already on the seismic behavior of dams. It is necessary that this information is adopted completely by the dam community. It is still much cheaper to make a dam to perform well during an earthquake in the design phase than having to upgrade it later. There is also the conviction of some people that a design must be safe when a similar design has already been used repeatedly in the past. However, we also have to recognize that (i) a bad design that has been used ten times in the past does not automatically become correct when carried out in the same way the next time, and (ii) the design of structures to resist extreme loads may never have been tested.

The design of a dam, which was considered as safe at the time it was approved may not be safe forever. This may be contradictory to the general opinion of owners and users of most buildings and structures. As earthquake engineering is still a relatively young discipline, design criteria, methods of analysis, design concepts, etc. may be subject to changes especially when a large dam, designed according to the current state of practice, is severely damaged during an earthquake. Thus, there is a need for periodic checks of the seismic design criteria and the earthquake safety of large dams (and other structures as well), i.e. budgets for periodic seismic safety checks must be considered. In general, dam owners and operators are reluctant to perform such checks unless there are laws and regulations and a dam safety organization that has the authority and means to ensure that the rules are followed. Again, the perception that what was once considered safe will remain safe forever is a dangerous misconception.

2 PSEUDOSTATIC ANALYSIS METHOD AND DEVELOPMENTS IN THE SEISMIC ANALYSIS AND DESIGN OF LARGE DAMS

All seismic loads were considered as static loads and, therefore, they could be analyzed in the same way as the other static loads, which made this analysis that is called pseudo-static analysis, quite simple. However, as mentioned before, when several dams were damaged during the 1971 San Fernando Earthquake, it became obvious that the pseudo-static method of analysis was no longer appropriate (Wieland, 2018a).

Why is the pseudo-static method obsolete? To answer this question, we only have to look at the dams that experienced cracks and inelastic deformations during strong earthquakes. If these dams were designed according to the pseudo-static method with stresses within the allowable stresses and the sliding safety factors exceeding the required values, then these dams should not have been damaged at all. This is not only due to the underestimate of the seismic coefficient but also due to the neglect of the dynamic response of the dams.

Since the 1930's when the pseudo-static analysis method was introduced for the seismic analysis of concrete and embankment dams, major developments in the seismic analysis and design of large storage dams have taken place. The main developments, documented in several ICOLD Bulletins, may be described as follows:

(i) Change from pseudo-static analysis to dynamic seismic analysis of dams,

(ii) Change from the representation of the earthquake ground shaking by a seismic coefficient to safety evaluation earthquake ground motion parameters,

(iii) Change from a single ground shaking hazard to multiple seismic hazards including ground shaking, mass movements, faulting, and project-specific and site-specific hazards, and

(iv) Change from the stability safety factor and allowable stress concepts to rational seismic performance criteria, characterized by dam deformations and seismic failure modes of dams.

In several countries and organizations, the obsolete seismic analysis concepts are still used. Because the pseudo-static analysis method is quite simple, and since it is used in seismic codes for buildings, many dam engineers are using and defending this outdated method, even in areas of high seismicity, where these deficiencies are most obvious.

Based on this brief overview, it may be concluded that for the seismic analysis and design of new dams modern seismic design and safety criteria should be used and all existing dams must be checked, if they comply with today‘s seismic design and safety criteria, which are the same for old and new dams. If not, they have to be upgraded or the reservoir level has to be lowered etc.

3 SAFETY EVALUATION OF EXISTING DAMS

There are many dams that have been built without taking into account earthquakes or which were designed against earthquakes using the pseudo-static analysis method. Therefore, it is not known if these existing dams satisfy today‘s seismic design and safety criteria.

In addition, seismic safety evaluations of existing dams have to be carried out repeatedly during the long life-span of a dam. There is a need for such safety checks in the following cases:

- New information on seismic hazard (multi-hazard) and/or seismo-tectonics is available;
- A dam has been subjected to strong earthquake shaking;
- New seismic design criteria are introduced;
- New seismic performance and safety criteria are introduced;
- New dynamic methods of analysis are introduced, such as nonlinear dynamic analysis methods;
- The seismic vulnerability of a dam has increased due to modifications, ageing etc., and
- Changes in risk classification of dams;
- The seismic risk has increased, e.g., due to the number of people living downstream of a dam having increased and due to economic development, etc.

It is obvious from the above list that there are quite a few reasons, why the seismic safety has to be reassessed. Ultimately, there is the requirement that regarding safety of the population, there should be no difference in the safety of people living downstream of a new or old dam. This means that all dams should satisfy the current seismic safety criteria. As this may not be the case, the reservoir may have to be lowered in the short-term but as this is not a long-term option for most dam owners, dam strengthening will be required.

Due to ongoing developments, it is also clear that seismic dam safety re-evaluations have to be carried out periodically for all dams. As the seismic hazard will not change suddenly and developments in dam engineering are relatively slow, such re-evaluations may have to be done approximately every 30 to 40 years.

The basic steps for the re-evaluation the seismic safety of embankment dams are as follows:

- Determination of the seismic failure modes of the dam due to different types of seismic hazard (see subsequent Section);
- Ground shaking hazard: Determination of the main parameters of the safety evaluation earthquake ground motion (i.e. acceleration response spectra, peak ground acceleration (PGA), duration of strong ground shaking in acceleration time histories);
- Estimate of dynamic material properties based on static and dynamic laboratory tests or information extracted from the literature;
- Dynamic analysis of a two- or three-dimensional finite element model of the dam-foundation system using, e.g., the equivalent linear method;
- Assessment of pore pressure build-up (liquefaction analysis for certain foundation conditions or materials in hydraulic fill dams);
- Calculation of permanent displacements of potential sliding masses along the dam slopes by, e.g., the Newmark sliding block analysis;
- Seismic settlement analysis (rough estimates can be made using empirical relations);
- Estimation of the freeboard reduction during the safety evaluation earthquake;
- Assessment of internal erosion hazard due to damage to the fine sand filter or to the waterproofing membranes etc.; and
- Seismic safety assessment based on the results of the earthquake analysis.

In the case of concrete dams, the basic steps for the seismic safety re-evaluation are as follows:

- Determination of the seismic failure modes of the dam due to different types of seismic hazard (see subsequent Section);
- Ground shaking hazard: Determination of the main parameters of the safety evaluation earthquake ground motion, which are the basis for dynamic analyses;
- Estimate of dynamic material properties of mass concrete and foundation rock;
- Modelling of joints whenever necessary;
- Dynamic analysis of a two-dimensional or three-dimensional finite element model of the dam-reservoir-foundation system;
- Dynamic stability analysis of concrete blocks separated by joints and/or cracks;
- Dynamic stability analysis of dam abutments; and
- Seismic safety assessment based on the results of the earthquake analysis.

The above dam analysis steps are applicable to the ground shaking hazard. For other earthquake hazards, other procedures may have to be followed. The main problem is that these hazards cannot be quantified as easily as ground shaking, which already includes major uncertainties. Different methods of dynamic analysis may be required as discussed by Wieland (2019).

In general, a screening would be needed in order to identify the dams with the largest seismic risk that have to be checked first.

The ICOLD Committee on Seismic Aspects of Dam Design has encouraged the member countries to carry out seismic safety evaluations of their existing dams. Usually, dam owners and operators are reluctant to perform seismic safety checks unless there are laws and regulations and a dam safety organization with the authority and means to ensure that the rules are followed. A thorough assessment of the design criteria is usually done when the dam owners are applying for a new concession for their project or are selling a dam. Again, the perception that a dam that was considered safe at the time of construction will remain safe forever is a dangerous misconception.

It has been this author’s concern to have a deeper look into the seismic safety of existing dams since he took over the chairmanship of the ICOLD Committee on Seismic Aspects of Dam Design in 1999. Since then, several countries have been motivated to evaluate the seismic safety of existing dams.

In the 1990s the seismic safety of more than 1200 dams under state supervision in California was checked (Babbitt, 2003). As a result of this comprehensive evaluation, 116 dams were identified as being deficient, including some severely damaged by earthquakes. Thus, safety improvements were required. The improvement ranged from various ways of structural strengthening (berming, buttressing, additional foundation treatment) to permanent or temporary storage restrictions, to dam removal in the most serious cases. Reservoir storage is reduced to improve safety as soon as analyses predicted unsatisfactory seismic dam performance. Storage restrictions were usually not considered as permanent solutions, unless gates were removed from outlets, spillway crests lowered, or other alterations made to ensure that the reservoir water surface does not rise above the restricted level.

In Switzerland, a seismic safety evaluation of all 208 large dams under government control was carried out by the dam owners (Darbre et al., 2019). The safety reports were submitted in 2013. The average age of the dams was about 70 years and most were designed to withstand earthquakes using a seismic coefficient of 0.1 and the pseudo-static analysis method. For this seismic safety check, the government authorities allocated a period of 10 years. There were a few dams with seismic safety problems, but these dams had already other types of safety problem or have shown unusual behavior under non-seismic conditions.

In various parts of the world, similar dam safety evaluation programs and actions are to be expected in the future. This is not only of considerable importance for countries with high seismicity but also for regions with moderate to low seismicity, as earthquake action may have been completely ignored in such places, so that the earthquake vulnerability of the dams may be higher than that of dams in highly seismic regions that were designed to withstand earthquakes.

Finally, it should be pointed out that in the seismic safety evaluation of dams, all elements of a comprehensive dam safety concept must be considered, i.e. structural safety (earthquake safety of dam and safety-critical elements; this paper is concerned with this topic only), seismic monitoring (strong motion instrumentation), operational safety (guidelines for the operation of the reservoir after an earthquake), and emergency planning (emergency action plan for earthquake hazard).

4 SEISMIC HAZARD

For large storage dam projects, the earthquake hazard is a multi-hazard, which includes the following (Wieland, 2009):

- Ground shaking causing vibrations in dams, appurtenant structures and equipment, and their foundations;
- Fault movements in the dam foundation or discontinuities in dam foundation near major faults, which can be activated, causing structural distortions;
- Fault movement in the reservoir bottom causing water waves in the reservoir, loss of freeboard and mass movements;
- Mass movements (rockfalls, landslides, rockslides) causing damage to gates, spillway piers (cracks), retaining walls (overturning), powerhouses, electro-mechanical equipment, penstocks, masts of transmission lines, electricity supply, etc., and blocking intake structures and access roads to dam sites and appurtenant structures;
- Mass movements into the reservoir causing impulse waves in the reservoir and overtopping of the dam;
- Ground movements and settlements due to liquefaction, densification of soil, causing distortions in dams, etc., and
- Project-specific and site-specific hazards.

Ground shaking is the main hazard considered in all earthquake codes, recommendations and guidelines, but fault movements in the footprint of concrete dams and mass movements may be even more dangerous. For example, the 2008 Wenchuan earthquake in China has shown that mass movements have been greatly underestimated in mountainous regions.

Water waves in the reservoir are often mentioned, but these waves are relatively small in large reservoirs subjected to strong ground shaking (amplitudes less than 1 m have been observed). However, important impulse waves could be generated by mass movements into the reservoir, especially when they occur close to the dam.

It must also be realized that for the seismic safety evaluation of almost all dams, models of earthquake ground motions are used that are not actual acceleration time histories, because by spectrum-matching even recorded acceleration time histories become “synthetic” as discussed by Wieland (2018). This concept may be difficult to understand or accept by seismologists as they are not familiar with dam engineering. Recorded acceleration time histories may only be used in exceptional cases, i.e. for the dynamic calibration of dam models, or for the reanalysis of a dam, whose strong ground shaking was recorded. Such records are rare as only few dams are equipped with strong motion instruments and up to now only few dams have experienced ground shaking similar to that expected from the SEE.

For the seismic analysis of dams the emphasis is on ground shaking. The numerical methods for the analysis of the other hazards listed above are much less developed than those used for the probabilistic and deterministic seismic hazard analyses.

5 SEISMIC DESIGN CRITERIA

The safety evaluation earthquake (SEE) ground motion 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 body, safety-critical components, and the stability of the dam abutments and reservoir banks where mass movements could plug intakes or create large impulse waves in the reservoir. The safety-critical elements are the gates of gated spillways and valves or gates of low-level outlets, which must be operable in order to control the reservoir level after the SEE (Wieland, 2017).

For design purposes, the operating basis earthquake (OBE) is also needed, but it is not relevant in the context of the seismic safety evaluation of dams.

The SEE ground motion can be obtained from a probabilistic and/or a deterministic seismic hazard analysis, 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. Its estimation is based on worst-case earthquake scenarios.
- Maximum Design Earthquake (MDE): For large dams the return period of the MDE ground motion parameters is taken as 10,000 years, which is based on a probabilistic seismic hazard analysis (PSHA).

For major dams the SEE can be taken either as the MCE or MDE ground motions. Usually, the most unfavorable ground motion parameters have to be taken.

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 recorded earthquake ground motions. The artificially generated acceleration time histories of the horizontal and vertical earthquake components must be stochastically independent. To account for aftershocks, it is recommended to increase the duration of strong ground shaking.

In the case of fault movements, the same estimates are required as for the ground shaking. It appears that it is quite difficult for dam engineers to get quantitative estimates of fault movements.

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. In the selection and/or definition of acceleration time histories of the SEE, the following factors should be considered:

- The three components of the spectrum-matched acceleration time histories may be assumed to be statistically independent.

- 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.
- The duration of strong ground shaking should account for aftershocks.
- In the case of dams, which are susceptible to damage processes that are governed by the duration of strong ground shaking, as e.g. the build-up of pore pressures or sliding movements, earthquake records with long duration of strong ground shaking, must be used.
- 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.
- For the safety check of a dam at least three different earthquakes must be considered for the SEE ground motion.

It should be added that for the seismic design of dams ground motion parameters are used, which do not necessarily have the characteristics that earth scientists feel are physically correct, i.e. duration of strong ground shaking, near field and directivity effects, spectrum shape of main and aftershocks, etc. However, the dam designer will use simplified load and analysis models that lead to a safe design, even if the load model does not comply with the real nature of the earthquake ground motion (Wieland, 2018b).

The seismic design criteria recommended in ICOLD Bulletin 148 (ICOLD, 2016) will remain for quite some time. However, the requirement that a large storage dam has to withstand the worst ground motion at the dam site will initiate further discussions as this concept is basically in contradiction to any risk-based design concepts. This discussion has been going on for many years, although this design philosophy has proven to be very successful and powerful, especially when the seismic safety has to be explained to the public. In this context, the following statement is still valid for the designers of any structure or project: We sell safety and not risk.

The above discussion applies to high consequence dams. In ICOLD Bulletin 148 (ICOLD, 2016), seismic design criteria are also given for moderate consequence and low consequence dams with return periods of the SEE ground motion parameters of 3000 and 1000 years, respectively. Several countries are using their own risk classification of dams, in which seismic design criteria are specified for each risk class. These design criteria may be different from those recommended by ICOLD.

6 SEISMIC SAFETY CRITERIA

A dam subjected to the SEE ground motion must satisfy the following safety criteria, in order to be declared earthquake safe (Wieland, 2019):

- retaining the reservoir and to protect people from the catastrophic release of water from the reservoir,
- controlling the reservoir level after an earthquake, as a dam could be overtopped and destroyed if the inflowing water into the reservoir cannot be released through damaged spillways or low-level outlets, and
- lowering the reservoir level after an earthquake (a) for repair works or (b) for increasing the safety of a damaged dam or when there are doubts about the safety of a dam.

These seismic safety criteria are different from those used in the past, when a dam was declared safe, when for different load combinations including static and seismic loads, the stresses were within the allowable stresses, the deformations were within allowable deformations, and the safety factors against sliding, overturning and others were larger than the safety factors specified in design guidelines.

More specifically, the SEE safety criteria for the dam body and safety-critical components and equipment are as follows:

- Dam body: Structural damage (cracks, deformations, leakage etc.) is accepted as long as the stability of the dam is ensured when there is no uncontrolled release of large quantities of water from the reservoir causing flooding in the downstream region of the dam.
- Safety-critical components and equipment: These components and equipment must be fully operable during and after the SEE. Minor distortions are accepted as long as they have no impact on the proper functioning of the components and equipment (Wieland, 2017).
- Abutment rock (important for arch dams): All abutment wedges must be safe.
- Reservoir slopes: no mass movements into the reservoir are accepted, which block intakes of the spillway or low-level outlets or which create large impulse waves in the reservoir that could cause overtopping of the dam crest. This requirement very important for embankment dams.

These latest seismic performance and safety criteria are not only important for dam engineers but also for hydro-mechanical and electro-mechanical engineers, who are in charge of safety-critical elements and who may not be aware of these new requirements.

The seismic safety of existing gated spillways must be checked taking into the account the ground motion transverse to the river flow direction. Usually the spillway piers have not been designed against such seismic actions. Also, low-level outlets are not provided in many dams. They are needed to cope with the possible effects of strong earthquakes. Hopefully, in future, we will no longer see dams without low-level outlets.

7 SEISMIC OBSERVATIONS OF DAMS

There are only few case histories where a concrete dam has suffered severe damage as a result of earthquake-induced ground motions. The best-known examples are the Hsinfengkiang buttress dam in China, the Koyna gravity dam in India, the Sefid Rud buttress dam in Iran, and the Shih-Kang concrete weir in Taiwan.

In the first three cases the damage pattern was similar, i.e. cracks appeared near the kink at the downstream face of the dams. Concrete dams will experience cracking mainly along horizontal working joints and some of the detached blocks may undergo limited sliding movements. The structures could be repaired and they are in operation, but the repair techniques differed somewhat. However, no further damaging earthquakes have occurred at these sites and the efficiency of the repair work could not be evaluated directly. These cases demonstrate the significant resiliency of concrete gravity and buttress dams to earthquake loading under the most severe conditions.

In the case of the Shih-Kang weir, which was located on an active fault, the main damage was caused by fault and surface movements. Unless special provisions are made, e.g. a joint that enables a certain amount of displacement, concrete dam blocks will rupture completely.

Regarding the seismic observations of embankment dams, the following conclusions may be drawn (Hinks et al., 2012):

- The worst damage has often been associated with liquefaction of embankment materials or of the foundations. Silty sandy materials are particularly susceptible to liquefaction.
- Material placed as hydraulic fill appears to be particularly vulnerable.
- Clay dams on clay foundations generally perform well when subjected to earthquakes.
- Rockfill dams generally perform well, particularly if well compacted.

8 CONCLUSIONS

The main conclusions are as follows:

- The dynamic analysis methods and the technology for designing and building dams that can safely resist the effects of strong ground shaking are available.
- Dams are not inherently safe against earthquakes.
- As most dams built prior to 1989 when ICOLD has published its seismic design criteria of dams, were designed to resist earthquakes using analysis methods, design and safety criteria, which are no longer in use, the safety of these dams is not known and it must be assumed that several do not satisfy today's seismic safety criteria. Therefore, owners of older dams must start with seismic safety checks of their dams.
- Seismic safety evaluations have to be carried out periodically during the long life-span of large dams.
- New information on the seismic hazard and new developments in the seismic design and safety concepts of large dams may require a re-assessment of the seismic safety of dams.
- Seismic safety evaluations include the dam body, gated spillways, low-level outlets, abutment wedges and reservoir slopes where mass movements could either block intakes of the spillway or low-level outlets or create impulse waves in the reservoir that could overtop the dam.

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