Seismic Design and Performance Criteria for Large Storage Dams

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SUMMARY:
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 large concrete and embankment dams. Earthquakes can cause multiple hazards in large dam projects including ground shaking, fault movements, rockfalls, landslides, landslide dams, liquefaction, water waves in reservoirs, etc. The integral seismic safety approach to be adopted for large storage dams is described. Furthermore, the seismic design criteria for large dams, safety-relevant elements, appurtenant structures, temporary structures and critical construction stages, recommended by the International Commission on Large Dams (ICOLD), are presented. The performance criteria of dams and safety-relevant elements such as bottom outlets and spillways, which must be operable after a strong earthquake, are discussed.

Keywords: Concrete dams, embankment dams, seismic design criteria, seismic performance criteria

1. INTRODUCTION

The seismic design criteria and methods of dynamic analysis of large concrete and embankment dams have undergone substantial changes since the 1930s when earthquake actions have been introduced to their design. At that time, the earthquake hazard was ground shaking, which was represented by a seismic coefficient. Typically, a value of 0.1 was used for most dams. In exceptional cases (e.g. Japan and Iran) slightly higher values were considered. The seismic coefficients had no clear physical relation with the design ground motions and the seismic hazard at the dam site. Moreover, the dynamic response was determined by a pseudostatic analysis, which does not account for the dynamic characteristics of the dam. Therefore, these design criteria and methods of dynamic analysis, which, due to their simplicity, are still liked by dam engineers, are considered outdated and may even be completely wrong. The seismic analysis and design of dams using seismic coefficients and the pseudostatic methods of analysis have been in use until the 1ate 1980s when the International Commission on Large Dams (ICOLD) published Bulletin 72 entitled ‘Seismic design parameters for large dams’ (ICOLD, 2010) in which it is stated that a dam should be able to resist the ground motions caused by the maximum credible earthquake.

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 analyses have been developed which allow the calculation of the inelastic seismic response of embankment and concrete dams. However, several strong earthquakes damaging dams such as the Chi-Chi earthquake 1999 (Taiwan), the Bhuj earthquake, 2001 (India), the Wenchuan earthquake, 2008 (China); and the Tohoku earthquake 2011 (Japan), have shown that earthquakes can cause multiple hazards including ground shaking, fault movements in dam foundations and reservoirs, rockfalls, landslides, landslide dams, liquefaction, water waves in the reservoir etc.

The dam safety concepts have also undergone changes and this had an impact on earthquake safety as discussed in the subsequent sections. In the past, dam safety was mainly related to structural safety, but today dam safety means structural safety, dam safety monitoring, operational safety and emergency planning. Such comprehensive dam safety concepts are necessary for large storage dams and public dam safety agencies are needed to enforce them. Unfortunately such agencies are still lacking in a number of countries.

Structural safety means design of a dam following internationally accepted guidelines for, e.g., flood hazard, earthquake hazard, seepage, and safety against other hazards from the natural and man-made environment including site-specific and project-specific hazards. In recent years the earthquake hazard has gained much importance in the dam industry.

In the earthquake-resistant design and construction of large dams and other infrastructure projects the following factors have to be taken into account:

- Selection of ground motion parameters of the different design earthquakes based on site-specific seismic hazard analyses, and selection of appropriate methods of seismic analysis;
- Observing conceptual and detailing recommendations for the earthquake-resistant design of dams; and
- High quality of all construction works.

To focus on dynamic analyses of dams is not the right way as it is not possible to make a dam with conceptual deficiencies to perform well during strong earthquakes by carrying out sophisticated dynamic analyses. Very often conceptual and constructional guidelines are more effective than analyses.

The paper provides an overview on the seismic design and safety of large storage dams. In particular, the seismic design criteria for dams, which have been approved by ICOLD in 2010, are presented. The paper is based on the author’s previous publications (Wieland, 2003; Wieland, 2006; Wieland, 2011) and ICOLD recommendations (ICOLD, 2001 and ICOLD, 2010).

2. ELEMENTS OF LARGE STORAGE DAMS FOR POWER GENERATION

A large storage dam consists of a concrete or fill dam with a height exceeding 15 m, 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 and the location of the project there are other components such as a power intake, desilting basin, underground structures, penstocks, powerhouse, switchyard, device for control of environmental flow, fish ladder, slopes, retaining walls, etc. These are mainly civil structures. In addition to that there are different types of hydro-mechanical equipment (gates, valves etc.) and electro-mechanical equipment for power generation and power transmission etc. Depending on their importance, all these structures and components must be able to withstand different types of earthquake actions, which are specified in the seismic design criteria.

3. EARTHQUAKE HAZARD: A MULTI-HAZARD FOR LARGE STORAGE DAMS

Recent earthquakes have demonstrated that major earthquakes are multiple hazard events, which can affect large dam projects in many different ways, i.e.

- 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 during strong nearby earthquakes causing structural distortions;

- fault displacement in the reservoir bottom causing water waves in the reservoir or loss of freeboard;
- rockfalls causing damage to gates, spillway piers (cracks), retaining walls (overturning), surface powerhouses (cracking and puncturing), electro-mechanical equipment, penstocks, switchyards, transmission lines, etc.
- mass movements (landslides and rockfalls) into the reservoir causing impulse waves and overtopping of dams;
- mass movements blocking rivers and forming landslide dams and lakes whose failure may lead to overtopping of downstream run-of-river power plants or the inundation of powerhouses and the electro-mechanical equipment;
- mass movements blocking access roads to dam sites and appurtenant structures, and
- ground movements and settlements due to liquefaction or densification of soil, causing distortions in dams and appurtenant structures, etc.

Most of the above hazards were observed during the May 12, 2008 Wenchuan earthquake in China.

Other effects in reservoirs such as surface water waves, long-period reservoir oscillations (seiches), turbidity currents, and tsunamis are generally of lesser importance for the earthquake safety of dams. The maximum water waves in reservoirs recorded during the March 11, 2011 Tohoku earthquake in Japan (magnitude 9.0) was less than half a meter. These surface waves can be compared with those caused by wind.

During impounding and/or during the first years of operation of large reservoirs reservoir-triggered seismicity (RTS) may occur, which is related to active faults in the reservoir region and/or the existence of faults with high tectonic stresses close to the strength of the fault.

Usually dam engineers are focusing on the ground shaking and tend to neglect the other seismic hazards, which for some dams may have consequences that are even worse than ground shaking. The consequences of the ignored hazards may be severe as they have not been considered in the design and thus the dam may be vulnerable to these hazards. Therefore, the analysis of all possible hazards is required. This can be done best by preparing a hazard matrix for each dam project in which for each structure, structural element and component the different seismic hazards are listed. For each structure and each relevant seismic hazard the design actions shall be given. For large civil structures subjected to ground shaking the protection against ground shaking is provided by the earthquake-resistant design. However, for important electro-mechanical components and smaller structures etc., which may have to function after a strong earthquake, base isolation or other types of damping mechanisms may be the proper solution.

Furthermore, the consequences of damaged or failed elements must be assessed as these may cause secondary hazards such as flooding due to penstock failure, fires etc.

Ground shaking affects all civil structures (above and below ground) and hydro-mechanical and electro-mechanical components of a large storage dam at the same time, whereas the other seismic hazards listed above may only affect certain types of structures or equipment. For example, the Wenchuan earthquake has shown that in the mountainous epicentral region, mass movement was a major hazard, which was underestimated in the design of hydropower plants. Also construction equipment could not be transported to several dam sites for several months because access roads were blocked by rockfalls. Therefore, it has to be assumed that a damaged dam has to remain safe for several months after an earthquake before it can be rehabilitated or transformed into a safe state.

4. INTEGRAL SAFETY CONCEPT FOR LARGE STORAGE DAMS

The main goals of every safety concept for large storage dam and infrastructure project are: (i) the minimization of all risks, and (ii) the mastering of the remaining risk in the best possible way.

To reach these two goals a comprehensive dam safety concept is needed. The main safety concern is the failure of a dam and the uncontrolled release of the reservoir water with flood consequences (loss of life, economical damage, environmental damage etc.), which will usually exceed the economical damage to the dam. Therefore, for the seismic risk assessment of a dam, full reservoir is the critical situation that has to be analyzed.

The seismic safety of a dam includes the following four elements:

1. Structural Safety: Strength to resist seismic forces without damage; capability to absorb high seismic forces by inelastic deformations (opening of joints and cracks in concrete dams; movements of joints in the foundation rock; inelastic deformation characteristics of embankment materials); stability (sliding and overturning stability), design of dam according to state-of-practice, etc.

2. Dam Safety Monitoring: Strong motion instrumentation of dam and foundation; visual observations and inspection after an earthquake; data analysis and interpretation; post-earthquake safety assessment, etc.

3. Operational Safety: Rule curves and operational guidelines for post-earthquake phase; experienced and qualified staff, etc.

4. Emergency Planning: Water alarm; flood mapping and evacuation plans; safe access to dam and reservoir after a strong earthquake; capability of lowering of reservoir after a strong earthquake; engineering back-up, etc.

In general, dams, which can resist strong ground shaking, will perform well also under other types of static and dynamic actions. It is obvious from the above list that earthquake-resistant design is only one element in the comprehensive safety concept of large storage dams.

A lot of know-how exists already on the seismic behaviour of dams. It is necessary that this information is fully used 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 made repeatedly in the past. However, we have to recognize that (i) a faulty design employed repeatedly in the past does not become correct when carried out in the same way the next time, and (ii) designs of structures to resist extreme loads may never have been tested (Wieland, 2006).

5. SEISMIC DESIGN CRITERIA FOR LARGE DAMS AND APPURTENANT STRUCTURES

The following design earthquakes are needed for the seismic design of the different structures and elements of a large dam project:

- 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 (2010) 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 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 (2010) 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.

- Safety Evaluation Earthquake (SEE): The SEE is the earthquake ground motion a dam must be able to resist without uncontrolled release of the reservoir. For major dams the SEE can be taken either as the MCE or MDE ground motions. Usually the most unfavourable 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. 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 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 (ICOLD, 2010). 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

MDE, DBE, OBE and CE ground motion parameters are usually determined by a probabilistic approach (mean values of ground motion parameters are recommended), while for the MCE ground motion deterministic earthquake scenarios are used (84 percentile values of ground motion parameters shall be used). However, for the MDE, DBE, OBE and CE also deterministic scenarios may be defined.

If reservoir-triggered seismicity (RTS) is possible then the DBE and OBE ground motion parameters 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.

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 movements for the different types of design earthquakes.

It must be added that for the seismic design of dams ground motion parameters are used, which do not necessarily have the characteristics, which the 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 fully with the real nature of the earthquake ground motion!

6. SEISMIC PERFORMANCE CRITERIA

According to ICOLD (2010) the performance criteria for the dam body and safety-relevant components and equipment are as follows:

- Dam body OBE: No structural damage (cracks, deformations, leakage etc.) which affect the operation of the dam and the reservoir is permitted. Minor, repairable damage, is accepted.
- Dam body SEE: Structural damage (cracks, deformations, leakage etc.) is accepted as long as the stability of the dam is ensured and no uncontrolled release of large quantities of water is released from the reservoir causing flooding in the downstream region of the dam.
- Safety-relevant components and equipment OBE: These components and equipments must be fully operable during and after the OBE. No distortions are accepted.
- Safety-relevant components and equipment SEE: These components and equipments 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.

The performance criteria may be linked to the definition of the SEE, e.g., sliding stability safety factors of slopes of greater than 1.0 are required for an SEE with a return period of 2500 years (Germany), or water stops in concrete dams shall not be damaged during the SEE with a return period of 5000 years (China). Such requirements may be stricter than those given by ICOLD (2010), especially in areas of high seismicity where the maximum earthquake ground motion parameters are already reached for events with return periods of less than 10,000 years.

Safety-relevant components and equipment are bottom outlets and spillways and all related equipment (mainly gates), control panels, power supply, software etc., as it must be possible to regulate and lower the reservoir after the SEE. As the repair of a damaged dam will need some time, it is necessary that after an earthquake a moderate flood with a return period of say 200 years can still be released safely. This may be a lesser problem for concrete dams, where limited overtopping of the crest may be acceptable under extreme circumstances, however, in the case of embankment dams such overtopping cannot be accepted, thus after an earthquake larger floods than for concrete dams must be considered.

For embankment dams the safety criteria under the SEE are: (i) loss of freeboard, i.e. after the earthquake the reservoir level shall be below the top of the impervious core of the dam, (ii) internal erosion, i.e. after the earthquake at least 50% of the initial thickness of the filter and transition zones must be available, and (iii) the sliding safety factor of slopes (considering build up of pore pressure and residual strength parameters of embankment materials) shall be larger than 1 after the earthquake.

The second criterion also applies for earth core rockfill dams located on faults or discontinuities in the dam foundation, which can be moving during a strong earthquake. Moreover, at such sites only conservatively designed earth core rockfill dams should be built.

7. EARTHQUAKE DESIGN ASPECTS OF CONCRETE AND EMBANKMENT DAMS

7.1 Concrete dams

There are several design details that are regarded as contributing to a favourable seismic performance of arch dams (ICOLD, 2001), (Note: Guidelines for the seismic design of appurtenant structures are given in ICOLD (2002)):

- Design of a dam shape with symmetrical and anti-symmetrical mode shapes that are excited by along valley and cross-canyon components of ground shaking.

- Maintenance of continuous compressive loading along the foundation, by shaping of the foundation, by thickening of the arches towards the abutments (filets) or by a plinth structure to support the dam and transfer load to the foundation.
- Limiting the crest length to height ratio, to assure that the dam carries a substantial portion of the applied seismic forces by arch action, and that non-uniform ground motions excite higher modes and lead to undesired stress concentrations.
- Providing contraction joints with adequate interlocking.
- Improving the dynamic resistance and consolidation of the foundation rock by appropriate excavation, grouting etc.
- Provision of well-prepared lift surfaces to maximize bond and tensile strength.
- Increasing the crest width to reduce high dynamic tensile stresses in crest region.
- Minimizing unnecessary mass in the upper portion of the dam that does not contribute effectively to the stiffness of the crest.
- Maintenance of low concrete placing temperatures to minimize initial, heat-induced tensile stresses and shrinkage cracking.
- Development and maintenance of a good drainage system.

The structural features, which improve the seismic performance of gravity and buttress dams, are essentially the same as that for arch dams. Earthquake observations have shown that a break in slope on the downstream faces of gravity and buttress dams should be avoided to eliminate local stress concentrations and cracking under moderate earthquakes. The webs of buttresses should be sufficiently massive to prevent damage from cross-canyon earthquake excitations.

The main factor, which governs the dynamic response of a concrete dam is damping. Structural damping ratios obtained from forced and ambient vibration tests are surprisingly low, i.e. damping ratios of the lowest modes of vibrations are of the order of 1 to 2% of critical. In these field measurements the effect of radiation damping in the foundation and the reservoir are already included. Linear-elastic dynamic interaction analyses of dam-foundation-reservoir systems would suggest damping ratios (structural and radiation damping) of about 10% for the lowest modes of vibration and even higher values for the higher modes of large concrete dams. Accordingly, the maximum dynamic tensile stresses in an arch dam might be up to 2 to 3 times smaller when all dynamic interaction effects are considered than those obtained from an analysis with 5% damping where the reservoir is assumed to be incompressible and the dynamic interaction effects with the foundation are represented by the foundation flexibility only (massless foundation). Unfortunately, there is a lack of observational evidence, which would justify the use of large damping ratios in seismic analyses of concrete dams.

Moreover, in view of the fact that large concrete dams will exhibit nonlinear behaviour (joint opening and cracking) during the SEE, the linear dam-reservoir-foundation interaction models are not applicable. Therefore, in view of the uncertainties in the estimation of the SEE ground motion, it is proposed to use damping ratios of maximum 5% for large arch dams and less than 7% for gravity dams when no other information and data is available.

7.2 Embankment dams

The seismic design of embankment dams is based on (i) conceptual (empirical) criteria, which are mainly based on the observation of the behaviour of embankment dams during strong earthquakes and the behaviour of soils and rockfill under dynamic loadings, and (ii) the results of seismic analysis of dams subjected to different types of design earthquakes, i.e. OBE and SEE. Usually several earthquakes must be analyzed – at least three. As a basis for the dynamic analysis, a static analysis that simulates the incremental construction of the dam body and the filling of the reservoir, and if applicable, a seepage analysis must be performed first before the earthquake ground motion can be applied.

The conceptual and constructional criteria for seismic-resistant fill dams are (ICOLD 2001):

- Foundations must be excavated to very dense materials or rock; alternatively the loose foundation materials must be densified, or removed and replaced with highly compacted materials, to guard against liquefaction or strength loss.
- Fill materials, which tend to build up significant pore water pressures during strong shaking must not be used.
- All zones of the embankment must be thoroughly compacted to prevent excessive settlements during an earthquake.
- All embankment dams, and especially homogeneous dams, must have high capacity internal drainage zones to intercept seepage from any transverse cracking caused by earthquakes, and to assure that embankment zones designed to be unsaturated remain so after any event that may have led to cracking.
- Filters must be provided on fractured foundation rock to preclude piping of embankment material into the foundation.
- Wide filter and drain zones must be used.
- The upstream and/or downstream transition zones should be ‘self-healing’, and of such gradation as to also heal cracking within the core.
- Sufficient freeboard should be provided in order to cover the settlement likely to occur during the earthquake and possible water waves in the reservoir due to mass movements etc.
- Since cracking of the crest is possible, the crest width should be wider than normal to produce longer seepage paths through any transverse cracks that may develop during earthquakes.

One of the most dangerous consequences of the dynamic loading of an embankment dam is the liquefaction of foundations or embankment zones that contain saturated fine-grained cohesionless and/or uncompacted materials.

The dynamic response of an embankment dam during strong ground shaking is governed by the deformational characteristics of the different soil materials. For large storage dams, the earthquake-induced permanent deformations must be calculated. The calculations of the permanent settlement of large rockfill dams based on dynamic analyses are still very approximate, as most of the dynamic soil tests are usually carried out with maximum aggregate size of less than 5 cm. This is a particular problem for rockfill dams and other dams with large rock aggregates and in dams, where the shell materials, containing coarse rock aggregates, have not been compacted at the time of construction. Poorly compacted rockfill may settle significantly during strong ground shaking but may well withstand strong earthquakes.

To get information on the dynamic material properties, dynamic direct shear or triaxial tests with large samples are needed. These tests are too costly for most rockfill dams. But as information on the dynamic behaviour of rockfill published in the literature is also scarce, the settlement prediction involves sensitivity analyses and engineering judgment (Wieland 2003).

At dam sites located on active or potentially active faults or discontinuities in the dam foundation, which can be moving during a strong earthquake, only conservatively designed earth core rockfill dams should be built. This means that in highly seismically active regions where there are doubts about possible movements along discontinuities in the dam foundation, earth core rockfill dams are the proper dam types.

8. LESSONS LEARNT FROM RECENT EARTHQUAKES

During the Tohoku earthquake of March 11, 2011 the 18.5 m high Fujinuma-ike embankment dam failed and the resulting flood wave killed 8 people. This is the first case of a dam failure caused by an earthquake, where lives of people were lost. Fujinuma-ike is an earthfill dam completed in 1949, storing a reservoir with 1.5 Mm^3, which was almost full at the time of the earthquake (Matsumoto et al., 2011).

Strong earthquakes can affect a large area and many dams may be subjected to strong ground shaking. This has been the case for the Wenchuan and Tohoku earthquakes. Different types of dams have been damaged.

During the Wenchuan earthquake mass movements (mainly rockfalls in very steep valleys) and landslide lakes were new hazards that were not considered in the design of dams and appurtenant structures. In addition, an unprecedented large number of dams and run-of-river power plants have been affected by this earthquake. The Wenchuan earthquake has confirmed and demonstrated that dams, spillways and appurtenant structures must be able to withstand the multiple effects of strong earthquakes. In particular the following items are important (Wieland and Chen, 2009):

- Following a strong earthquake the seismic hazard at dam sites and seismic design guidelines had to be reassessed, reviewed and updated.
- In mountainous regions mass movements have to be expected, which hinder access to dams after an earthquake up to several months, and rockfalls can cause substantial damage to surface appurtenant structures and hydro-mechanical equipment.
- The earthquake hazard has several site-specific features, which must be considered in the design of new dams or the safety evaluation of existing dams.
- Safety-relevant gates and gate structures must be operable after strong earthquakes
- The concrete face of concrete face rockfill dams are vulnerable to strong ground shaking mainly due to large in-plane forces. They can be reduced significantly by providing adequate joint widths and detailing of joints as well as reinforcement of the concrete slab.
- Seismic instrumentation is still lacking in most large dams.
- Methods for the assessment of the seismic safety of slopes need further development
- Every time a strong earthquake occurs, new features show up which have been overlooked in the past by dam engineers.

8. SEISMIC SAFETY EVALUATION OF EXISTING DAMS

There are two cases, which call for the safety evaluation of existing dams (Wieland, 2006):

- when a strong earthquake has occurred and strong motion instruments have recorded strong shaking in a dam and a post-earthquake inspection has revealed some damage, and
- when the seismic design criteria or seismic performance criteria have changed and/or new developments have taken place (a) in the seismic hazard assessment, (b) in the methods of seismic analysis, or (c) in the dynamic behaviour of materials, etc.

Thus, during the lifespan of a dam several seismic analyses may be needed. As most dams built prior to 1989, when ICOLD has published guidelines on seismic design criteria for dams (ICOLD, 2010), were designed for earthquakes using seismic design criteria and methods of dynamic analyses, which are considered as obsolete today, it has become necessary to re-evaluate the seismic safety of these dams. Such evaluations have been done or are under way in several countries. But eventually all the older dams have to be checked using modern seismic design criteria and methods of dynamic analysis.

9. CONCLUSIONS

The seismic hazard is a multi-hazard for most dam projects. Ground shaking is the main hazard considered in all earthquake guidelines for dams. The other seismic hazards are addressed less rigorously than the ground shaking or may even have been ignored.

Fault movements in the footprint of a dam are the most critical seismic hazard for most dam types. If no other site can be selected then a conservatively designed earth core rockfill dam would be the only solution.

Dams are not inherently safe against earthquakes. However, the technology for designing and building dams and appurtenant structures that can safely resist the effects of strong ground shaking is available.

The concrete slab of concrete face rockfill dams is susceptible to seismic settlements and large in-plane stresses if it acts as a monolithic structure. Open joints can almost completely eliminate these stresses resulting from the greatly different deformational behaviour of the rockfill and the concrete.

As most dams built prior to 1989 when ICOLD has published its seismic design criteria of dams (ICOLD, 2010)], have not been checked for the SEE ground motion, the earthquake safety of these dams is not known and it must be assumed that a number of them do not satisfy today's seismic safety criteria. Therefore, owners of older dams shall start with the seismic safety checks of their dams.

Today we have to recognize that

- the earthquake load case has evolved as the critical load case for most large dams even in regions of low to moderate seismicity,
- due to changes in the seismic design criteria and the design concepts it may be necessary to perform several seismic safety checks during the long economical life of a large dam,
- our knowledge on the behaviour of large dams during strong ground shaking is still very limited, and
- each destructive earthquake affecting dams may reveal some new features, which up to now may have been ignored.

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REFERENCES

ICOLD (2001). Design features of dams to effectively resist seismic ground motion, Bulletin 120, Committee on Seismic Aspects of Dam Design, International Commission on Large Dams, Paris.

ICOLD (2002). Earthquake design and evaluation of structures appurtenant to dams, Bulletin 123, Committee on Seismic Aspects of Dam Design, International Commission on Large Dams, Paris.

ICOLD (2010). Selecting seismic parameters for large dams. Guidelines, Revision of Bulletin 72, Committee on Seismic Aspects of Dam Design, International Commission on Large Dams, Paris.

Matsumoto, N., Sasaki, T. and Ohmachi, T. (2011). The 2011 Tohoku earthquake and dams, Proc. Int. Symp. on Dams and Reservoirs under Changing Challenges, Schleiss & Boes (Eds). 79th Annual Meeting of ICOLD, Swiss Committee on Dams, Lucerne, Switzerland, June 1.

Wieland, M. (2003). Seismic aspects of dams, General Report, Q.83 Seismic Aspects of Dams, Proc. 21st Int. Congress on Large Dams, ICOLD, Montreal, Canada.

Wieland M. (2006). Earthquake safety of existing dams, keynote lecture, Proc. First European Conference on Earthquake Engineering and Seismology, 1ECEES, (a joint event of the 13th European Conference on Earthquake Engineering & 30th General Assembly of the European Seismological Commission), Geneva, Switzerland, 3-8 September.

Wieland, M. and Chen, H. (2009). Lessons learnt from the Wenchuan earthquake, Int. Journal Water Power and Dam Construction, September.

Wieland, M. (2011). Seismic safety of large storage dams, Proc. High-level Forum on Safe Construction and Risk Management of High Dams and Large Reservoirs, IWHR and CHINCOLD, Beijing, China, Sep. 24-25.