Changes to expect in seismic safety assessment of large storage dams in future

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ABSTRACT:

Since the 1930s, when the pseudostatic seismic analysis methods for concrete and embankment dams were introduced, the following 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 concept to rational seismic performance criteria, characterized by dam deformations. There are still considerable uncertainties about the behaviour of a dam under very strong ground shaking. The following topics are discussed that need further attention: inelastic earthquake behaviour of dams under strong ground shaking; seismic strengthening of existing dams; short-term behaviour of mass concrete, RCC and rockfill materials; seismic design of hydro-mechanical and electro-mechanical equipment; abutment stability of arch dams during earthquakes; seismic behaviour of asphalt core rockfill dams and other new types of dams; seismic safety of tailings dams during operation and long-time storage phase, and seismic design and performance criteria. These seismic safety aspects of dams are discussed in the paper.

1 INTRODUCTION

The first modern dams that experienced strong ground shaking were those affected by the 1906 San Francisco earthquake. At that time no seismic loads were considered in the analysis and safety checks of dams and the designs were based on empirical criteria. Rational seismic analysis concepts for concrete dams were used in the 1930s for the construction of Hoover dam in the USA (Westergaard, 1936). At the same time a method for the seismic slope stability analysis was proposed by Mononobe et al. (1936). For both types of dams the seismic hazard (ground shaking) was represented by a seismic coefficient. Typically a value of 0.1 was used, almost irrespective of the seismic hazard at the dam site. For concrete dams the horizontal inertia force of the mass concrete was taken as the product of the seismic coefficient times the dead load of the dam and the hydrodynamic pressure from the reservoir was taken into account assuming incompressible behaviour of water. For embankment dams the earthquake load was represented by the horizontal inertia load acting in the most unfavorable direction in the center of gravity of the sliding mass. 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 pseudostatic analysis, quite simple. This was the international state-of-practice until 1989, when ICOLD published its first modern guideline on “Selecting Seismic Parameters for Large Dams” (ICOLD, 1989). However, already in 1971, when several dams were damaged during the San Fernando Earthquake in California, it became obvious that the pseudostatic method of analysis was no longer appropriate (Wieland, 2018a).

Why is the pseudostatic method obsolete? To answer this question we only have to look into the dams, which experienced cracks and inelastic deformations during strong earthquakes. If these dams have been designed according to the pseudostatic 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 a result of the underestimate of the seismic coefficient but also due to the neglect of the dynamic response of the dams.

Different research works on the seismic analysis and behaviour of dams started already before the San Fernando earthquake, but these dynamic methods were only used in special cases.

Since the 1930s considerable 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 pseudostatic 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 the single ground shaking hazard to multiple seismic hazards including ground shaking mass movements, faulting, etc. and

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

In several countries and organizations, the old seismic analysis concepts are still used although they have been considered as obsolete and even wrong since the time of the San Fernando Earthquake in 1971. Because the pseudostatic analysis method is that 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.

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

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 shall 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 (Wieland, 2016). If not they have to be upgraded or the reservoir level has to be lowered etc.

As earthquake engineering is still a relatively young discipline and since large dams have to be able to withstand the strongest ground motion at a dam site, there is a need for periodic reviews and checks of the seismic design and safety criteria and the seismic safety according to the current state-of-practice. Still, there are major uncertainties in the estimated seismic ground motion parameters and none or very little information exists on the seismic performance of new types of dams during strong earthquakes as, for example, asphalt core rockfill dams, concrete-face rockfill dams and others, which, today, are popular among dam engineers. Therefore, we cannot only focus on the current state-of-practice, documented, e.g., in ICOLD guidelines. It should also be pointed out that the criteria given in these guidelines are minimum requirements and that for special problems engineers have to use more advanced seismic safety concepts or even new ones.

Moreover, if we talk about the future, we think about a time frame of 10 to 20 years, which corresponds to the time intervals new seismic guidelines should be updated. This seems to be a long period, but as mentioned before, it takes still a long time until new safety concepts are introduced in all countries. For example, the check of the seismic safety of existing dams, which was recommended by the author, when he was appointed Chairman of the ICOLD Committee on Seismic Aspects of Dam Design in 1999, has only been done in a few countries. Seismicity at dam sites is hardly changing within short periods of time, but it is the knowledge on the seismic hazard that changes and new information on the seismicity and seismotectonic environment may become available. The seismic safety checks are usually delayed or postponed because of economic constraints rather than lack of manpower or knowledge. If the dam safety authorities do not request safety checks, dam owners tend to do the minimum as there are no direct economic benefits of dam safety reviews and/or the seismic upgrading of dams. This is not new.

2 SEISMIC HAZARD EVALUATION OF DAM SITE

For large storage dam projects, the earthquake hazard includes (i) ground shaking, which is the main hazard considered in seismic design codes and guidelines, (ii) displacements along potentially active faults in the dam foundation and/or the reservoir, (iii), landslides and rockfalls, which may cause impulse waves in the reservoir, block intakes of low-level outlets and spillways or may damage important equipment and installations at or close to the dam site or block access roads to the dam, and (iv) other site-specific and project-specific hazards.

Moreover, as strong earthquakes are rare events, the earthquake hazard is one of the least known hazards. In particular, the estimate of the ground motion at the dam site for the strongest earthquakes with a very low probability of occurrence is difficult and associated with major uncertainties. Therefore, a thorough investigation of the geologic and seismotectonic setting of the dam and reservoir region is required, which is part of any deterministic and probabilistic seismic hazard assessment.

Today, the seismic hazard studies focus on ground shaking. This is an important earthquake hazard, but the other seismic hazards must be analyzed to the same extent in future. The methods of seismic hazard analyses have made great process within the last 20 to 30 years and the models used are getting more and more complex. A lot of research is done in this field and changes are expected in the future. However, large uncertainties will remain at most dam sites, simply due to the fact that the earthquake catalogues are too short, e.g., for the reliable prediction of ground motion parameters with return periods of 10,000 years.

The main future developments in the ground shaking hazard relevant for large dams include the following items:

(i) evaluation of ground motion parameters of strong near-field earthquakes,

(ii) evaluation of site-specific geological and topographic effects on ground motion parameters,

(iii) evaluation of directivity effects on ground motion parameters at dam sites,

(iv) definition of duration of strong ground shaking of different design earthquakes,

(v) development of site-specific (spectrum-matched) acceleration time histories used for the seismic safety assessment of dams, and

(vi) development of non-uniform ground motion models for dams.

There are other factors that are important for seismologists but of lesser importance for dam engineers. It is essential that seismologists provide the ground motions required by dam engineers and that they make the dam engineers aware of new developments in ground motion prediction that may have a negative effect on dam safety.

From the above items, item (v) is the most important one for dam engineers, as for their seismic analyses, they need acceleration time histories as input. As the inelastic deformations in dams, the build-up of pore pressure in soils and other damage mechanisms depend on the duration of strong ground shaking; therefore, acceleration records with long duration of strong ground shaking are needed for a conservative design and safety assessment of dam projects. By using extended durations of strong ground shaking, the effects of aftershocks can be included, without requiring extra analyses.

Non-uniform ground motion models (item vi above) are still in the early research stage and there is a lack of simple models that could be used by dam engineers for their large dam projects. Of course, one could include the geologic and seismotectonic conditions and the earthquake mechanism in a dam-reservoir-foundation model, but such models are not yet used for dam design, as due to the many uncertainties, numerous sensitivity analyses would be necessary. Also the finite element models of the dam body would be too coarse in such analyses, and the cost of such analyses would also exceed any budget for dam analysis. Such ideas have existed for about 50 years, in parallel with the development of the finite element method and the availability of computers.

The design ground motions required by dam engineers that allow them to design safe dams may be quite different from recorded earthquake ground motions as discussed by Wieland (2018b). Seismologists, who want to provide "exact" ground motions, may not be aware of the fact that for the seismic design and safety checks, so-called ground motion models are used rather than exact ground motions. The concept of ground motion models is equivalent to that of load models used in the design of buildings and bridges by engineers for over 100 years, and this concept has proven to be very powerful in practice. Here a better understanding among seismologists and dam engineers is necessary in future. This aspect is important as it creates much misunderstanding. As the seismic design and earthquake safety assessment of dams is the core competence of dam engineers, the seismologists should deliver what the dam engineers need.

For seismic hazard characterization the following developments have taken place or may be anticipated in the future:

(i) Seismic coefficient: This is the first ground motion model used in which the earthquake ground motion (acceleration time history) is characterized by a seismic coefficient that represents the peak ground acceleration (PGA). However, there is no sound scientific basis between the seismic coefficient and the PGA and it is not clear what level of design ground motion it represents. The seismic coefficient model is still used for the design of large dams, although this is an outdated model.

(ii) Ground motion parameters determined from probabilistic and/or deterministic seismic hazard analyses: Typically, the acceleration response spectra are calculated for different return periods and confidence levels. Spectrum-matched acceleration time histories are determined, as they are required as input for the seismic analysis of dams. The acceleration time histories are not real earthquake ground motions and have to be considered as ground motion models, as discussed before. This represents the present stage in the seismic analysis of dams. The seismic hazard analyses (ground shaking hazard) have become very sophisticated as compared to (i).

(iii) Future ground motion models: For future ground motion models used in the dam industry, the probabilistic seismic hazard analysis approach will be suitable for determining the ground motion parameters for "usual" design earthquakes. However, for the SEE ground motion, we can see the following approaches: (a) use of present methods discussed in (ii), taking into account new developments, or (b) an upper bound magnitude and focal depth are specified as area source. To some extent (b) would correspond to the above seismic coefficient approach. No recurrence period would be assigned to such "floating" earthquakes, which as a worst case could occur directly beneath the dam. Floating earthquake scenarios are nothing new. They are assumed, for example, in the Zagros Mountain Range in Iran, where at a depth of 10 km a rock salt layer exist where earthquakes (reverse faulting mechanism) with moment magnitudes of 5.8-6.5 were specified, considering the magnitude of past earthquake in the project region. The advantage of (b) is that the seismic hazard analysis would be much simpler than that used today. Today's probabilistic seismic hazard analyses (ii) are becoming more and more advanced without actually contributing to the improvement of the seismic safety of dams.

3 SEISMIC DESIGN CRITERIA

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 with any risk-based design concepts. This discussion has been going on for many years and will hardly be resolved, 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.

As far as dam safety of existing older dams is concerned and this includes seismic safety, there shall be no difference in the safety of people living downstream of an old or new dam. This implies that all dams must satisfy today‘s safety criteria. This is a very ambitious goal, which has not been reached yet in many parts of the world. Therefore, this is a long-term task for the future, but there is nothing new with this. It must be done.

The main issue related to the seismic design criteria, which are specified for three types of dams (ICOLD, 2016), i.e. extreme or high consequence dams, moderate consequence dams, and low consequence dams, is the risk classification of dams. There are significant differences in the risk classification used in different countries and organizations. If the same dam is, for example, classified as a high risk dam in one country, which must resist the ground motion of an earthquake with a recurrence period of 10,000 years (ICOLD, 2016) may be classified as a moderate consequence dam in another country, requiring a recurrence period of the safety evaluation earthquake (SEE) of 3000 years or even 1000 years for low consequence dams. Future developments must address this issue. Risk-based approaches may be used, but for densely populated countries in Europe, where the failure of any large dam has high consequences, this approach may not be feasible.

Although ICOLD recommends a recurrence period of the SEE of 10,000 years for high consequence dams, other recurrence periods are specified in some countries, i.e. 2475 years, similar to the reference return period used in seismic building codes in North America. More flexible criteria for the return period may be provided in future for dams located in areas of different seismicity. In some areas of low seismicity return periods of 30,000 years have been considered for very large dam projects (U.K., Ethiopia).

An important aspect of the seismic design criteria is the definition of the seismic load combinations, which form the basis of any seismic analyses (Wieland, 2019), which may have to be updated based on future safety requirements and due to new knowledge about possible seismic failure modes of dams. There is also the question of higher safety standards for dams forming dam cascades along rivers and other projects with extreme consequences.

4 SEISMIC PERFORMANCE CRITERIA

If we use modern seismic design criteria for large dams (ICOLD, 2016), the following, very general, performance criteria apply for the effects of the strongest ground motion at a dam site:

(i) to retain the reservoir and to protect people from the catastrophic release of water from the reservoir,

(ii) to control 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

(iii) to lower the reservoir level after an earthquake (i) for repair works or (ii) for increasing the safety of a damaged dam or when there are doubts about the safety of a dam.

These seismic performance 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. This concept has been used in the past and is still being used by some engineers today.

These new seismic performance criteria have far-reaching consequences, which go beyond the tasks of dam engineers – mainly civil engineers -, because functionality of gates of spillways and low-level outlets is the main task of hydro-mechanical and electro-mechanical engineers, who may not be aware of these new requirements. Therefore, in future, there is a need to have a broader look at the seismic safety of dams and to include the functionality of safety-critical hydro-mechanical and electro-mechanical components. There is a need to adjust the design guidelines for hydro-mechanical and electro-mechanical components of spillways and low-level outlets. These components must be designed for the SEE ground motions at the support of these components.

The seismic safety of the 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 see more dams with low-level outlets.

5 METHODS OF SEISMIC ANALYSIS OF DAMS

5.1 *Nonlinear dynamic analysis of dams*

Today, most seismic analyses carried out by dam analysts are linear-elastic dynamic analyses (ICOLD, 1986), assuming that the foundation is massless and the water in the reservoir is incompressible. The advantage of such analyses is that they are quite simple and if the same material parameters are used, two dam analysts using different computer programs would obtain the same results. However, in view of today‘s seismic design and performance criteria, where inelastic deformations are accepted when a dam is subjected to the SEE ground motions, nonlinear analysis models have to be used, as, for example, it would not be possible to economically design a concrete dam, where the dynamic tensile stresses obtained from a linear-elastic dynamic analysis do not exceed the dynamic tensile strength of mass concrete in the whole dam.

The simplest nonlinear analysis models are of the dynamic stability analysis type, originally proposed by Newmark for the sliding block analysis of embankment dams. In concrete dams, block joints are modelled as well as cracks along the dam-foundation contact. In general, a so-called post-cracking analyses is carried out in concrete dams, in which it is assumed that cracks have fully developed, i.e. that they have propagated along lift or construction joints from the upstream to the downstream dam face etc. (Malla & Wieland, 2003). These discrete crack models are the simplest models for the nonlinear seismic analysis of concrete dams.

The methods for nonlinear dynamic analysis of dams are, however, still under development. Nonlinear seismic analyses need substantial engineering judgment. Relatively simple models should be preferred to complex models employing nonlinear constitutive laws using parameters that are either not available or very hard to determine. These developments have been going on for several decades already and a dramatic change in the models used by dam engineers is not expected in the near future, except for special cases. Again, the main problems are the high cost of such analyses, which due to uncertainties in the parameters of the nonlinear constitutive models will require extensive sensitivity analyses. However, changes are expected in line with the implementation of the new seismic design and performance criteria discussed in the previous sections.

Dynamic stability analysis methods are also needed for the safety check of abutment wedges. This is of main concern for arch dams, which are vulnerable to foundation movements.

5.2 *Concrete dams*

There are several commercial general purpose computer programs, which can be used for the nonlinear dynamic analysis of dam-reservoir-foundation systems. They are mainly applicable to concrete dams. There are other geotechnical programs that are suitable for embankment dams.

An important, still not properly resolved issue is the effect of dynamic dam-foundation interaction. In linear-elastic stress analyses, the maximum dynamic stresses of an idealized homogeneous massed foundation may be significantly smaller than those obtained from a massless foundation model. Therefore, some analysts prefer massed foundation models with energy-absorbing boundaries, which, however, are not provided in general purpose analysis software. Problems are due to the geology and material properties of the foundation rock. Jointed rocks, rock anisotropy, geology, topography and other factors may limit wave radiation in the foundation. Therefore, massless foundation models are normally used by dam analysts for both the linear and nonlinear dynamic analysis of arch dams. Such relatively simple dam-foundation analyses, whose results are assumed to be on the safe side, are also more economical than the analysis of advanced dynamic dam-foundation models. Some future developments are expected, but in general, only models, which can be easily implemented in general purpose software, will be successful.

Another issue for concrete dams is the damping ratio. The values proposed in some guidelines for the linear-elastic dynamic analysis of concrete dams vary from 5% to more than 12% for strong ground shaking. In nonlinear dam models, where damping is also caused by nonlinear deformations, the structural damping should be less than 5%, a value that is representative for the linear dynamic analysis for arch dams, which includes radiation damping into the reservoir and the foundation rock. With the increased number of dams equipped with strong motion instruments, records will eventually become available, which allow the determination of better damping ratios. It must be kept in mind that the damping ratio is the most important dynamic material property that governs the dynamic response of concrete dams.

5.3 *Embankment dams*

For the seismic analysis of embankment dams the linear-equivalent method with shear strain dependent shear modulus and damping ratio is still used by most dam consultants, although this method is already more than 50 years old. This method, in combination with the Newmark sliding block analysis of critical wedges in embankment dams, does not provide reliable information on the inelastic seismic deformations of the dam. For earth and rockfill dams, and dams with a flexible upstream geomembrane or asphalt facing, the results from this simplified method allow a conservative assessment of the safety against overtopping and the safety against internal erosion embankment dams with filter.

However, new types of dams like concrete-face rockfill dams (CFRDs), asphalt core rockfill dams, and dams with core walls made of (plastic) concrete, where the waterproofing elements are very thin compared to the thickness of the core of an earth core rockfill dam, are vulnerable to dam deformations, which may be of the same order or even larger than the thickness of the waterproofing elements. In CFRDs it is the great difference in stiffness between concrete and rockfill, which creates high in-plane stresses in a concrete face, and in asphalt core dam, sliding movements of wedges may damage the thin asphalt core, although it is very flexible in bending but not necessarily in shear. Similar problems are encountered in concrete core walls.

Therefore, computer programs are needed, which allow the reliable prediction of the inelastic seismic deformations of these new types of dams, which are already built even in highly seismic regions; therefore, such software is urgently needed.

6 DYNAMIC MATERIAL PROPERTIES

The study of dynamic material properties and constitutive models for concrete, soils and rock is basically a long-term research field. Most available information is related to the dynamic material properties of concrete and rock, the shear strength of joints, and the shear strain dependent shear moduli and damping ratios of soils, which are required in the different types of dynamic analyses of dams. The uncertainties in material properties or even lack of them require extensive sensitivity analyses. New results for mass concrete, RCC and soils are expected. For concrete dams, as pointed out earlier, the main interest is in the damping ratio, which controls the dynamic response.

7 SEISMIC INSTRUMENTATION OF DAMS

In the seismic instrumentation of large dams we have to note the following (Wieland, 2009):

(i) The seismologists and some dam analysts want to have most stations located in the free-field and in the abutments so they can reanalyze the dam with the recorded ground motions.

(ii) The dam engineers want to understand the seismic behaviour of the dam under strong earthquakes; therefore, they need instruments in the dam body and not in the dam foundation. However, for the calibration of finite element models as many stations as possible are needed in the dam body and the dam foundation.

The absolute minimum number of instruments is two, i.e. one at the base of the dam and the other on the crest. This is the concept used in Japan.

The main questions to be answered by strong motion instruments are as follows:

(i) What is the damping in concrete dams under strong ground shaking (in many dynamic analyses a value is assumed which may have no relation with reality, i.e. by selecting high damping ratios the dynamic response can be reduced substantially)?

(ii) What is the amplification of the ground acceleration with respect to the crest of the dam?

(iii) What is the variation of the ground motion along the abutments (mainly of arch dams) in steep and narrow valleys?

Besides accelerometers other instruments can be used to monitor inelastic deformations (pendulums, joint meters, geodetic measurements, tiltmeters, etc.) and changes in the ground water regime (piezometers, pressure cells, seepage measurements, etc.).

In the case of large reservoirs where reservoir-triggered seismicity may occur, it is recommended to install a microseismic network in the dam and reservoir region, which should be in operation at least two years prior to the start of dam construction to measure the background seismicity, and seismic monitoring should cover the phase of the first filling of the reservoir and the subsequent years of reservoir operation.

Strong motion instrumentation of large dams has other benefits as they can also be used (i) for health monitoring of the dam (monitoring of changes of eigenfrequencies with time), (ii) for alarm purposes, and (iii) for the verification and improvement of the seismic design criteria.

The benefits of seismic instruments in dams have not yet been exploited fully. We strongly recommend the installation of such instruments in all large dams. The priority should be given to dams located in highly seismic regions, very large dams with large reservoirs, dams, which have shown signs of unusual behaviour, dams that have experienced strong ground shaking, dams that are vulnerable to ground shaking, and new types of dams like CFRDs, RCC dams, asphalt core rockfill dams and others. Therefore, we expect that more dams will be equipped with strong motion instruments in future. These instruments need proper maintenance and the records must be properly evaluated. We have to keep in mind that engineers in charge of dam safety and dam owners are only interested in strong ground shaking and not in minor earthquakes.

8 FUNCTIONAL RECOVERY AND OTHER ASPECTS

8.1 *Functional recovery after earthquakes*

Functional recovery is gaining increasing importance. It is basically a performance criteria issue of the hydro-mechanical and electro-mechanical equipment. In the case of safety-critical equipment for gated spillways and low-level outlets, functionality is required during and after the strongest ground shaking (Wieland, 2017), as the top priority is dam safety and the protection of the people living downstream of large storage dams from the catastrophic release of water from the reservoir.

Multi-purpose storage projects may include hydro-mechanical and electro-mechanical equipment for power generation, operation of ship locks used for navigation, and operation of water supply and irrigation systems, etc. Although, these are not safety-critical elements, which affect the dam safety, functional recovery of these facilities is important. Of course, the time for the repair of damaged equipment may take a lot of time when spare parts are not available and when heavy equipment has to be replaced. Access roads to powerhouses may be blocked due to rockfalls in mountainous regions, as experienced, for example during the 2008 Wenchuan earthquake in China. The type of possible damage is manifold. The most effective way for improving the seismic safety and thus the functionality of this equipment would be to specify higher seismic safety levels. As large storage projects are subjected to different hazards from the natural and man-made environment, functionality is not only a concern for the earthquake hazard, which may not be the most critical one, but for all of them. Therefore, focusing on strong earthquakes, which may never occur, is not the solution. Functionality, is a matter to be dealt with in internal emergency action plans.

8.2 *Cut-off walls*

Cut-off walls in soils may be made of plastic concrete, which, due to creep effects have similar long-term static stiffness characteristics like the surrounding soil. However, there is a need to study the stiffness of plastic concrete under seismic strain rates as creep effects will be greatly reduced, causing stiffening of the plastic concrete and changes in the dynamic behaviour.

8.3 *Risk analysis*

Risk-based seismic safety studies of large dam projects have been proposed for quite some time, but progress is slow. The probabilistic description of the ground shaking hazard is standard practice today. However, as the seismic hazard is a multi-hazard the other seismic hazards like faulting, rockfalls and landslides etc. must be included in such analyses to be meaningful, but the probabilistic characterization of these hazards is less advanced than that of the ground shaking hazard.

Further developments are expected in the future, which include the analysis of the seismic vulnerability of dams up to failure. The corresponding nonlinear dynamic analyses are still a great challenge. Shaking table tests would be an alternative, but they are only done for very few important dams, mainly in China. The use of theoretically derived fragility curves to describe the seismic vulnerability of dams is too simplistic. One of the terms of reference of the ICOLD Committee on Seismic Aspects of Dam Design some 20 years ago, was related to the seismic risk of dams. But due to the difficulties in defining the seismic vulnerability of different types of dams, which ultimately depends on the quality of the design and construction works, no real progress could be achieved and this subject had to be postponed. It has not yet been solved, but future developments are expected.

The present seismic risk analyses are mainly concerned with ground shaking and need further improvement. However, the seismic design of dams and the analysis of the earthquake safety of dams is still based on deterministic concepts. Due to the limitations of risk-based analyses, stress tests are required, in industries, which rely on risk analysis. These stress tests are done, e.g., for nuclear power plants, and include earthquake scenarios.

9 CONCLUSIONS

The seismic safety assessment of a dam includes the following main subjects: seismic hazard analysis, selection of seismic design criteria, modelling of dam-reservoir-foundation systems, determination of material models and dynamic material properties, methods of nonlinear seismic analysis, and definition of seismic performance criteria. All of them vary with time. Therefore, it is necessary to review the seismic safety assessment periodically. It is obvious that in a comprehensive safety review all other hazards must be included as well. This is the main task for the future. This periodic review concept is not new, but it is very useful and should be implemented by all dam owners and dam safety authorities. By this concept, effects of the widely discussed climate change on dam safety can also be assessed. If the safety criteria are not satisfied, then remedial actions have to be taken. Such detailed reviews should be done every 5 years, as for example in Switzerland. In practice, a reanalysis of the seismic safety may only be needed when the bases of the analysis and/or the safety criteria have changed significantly, which may be in the time frame of 20 to 40 years – not every five years.

In future new developments may be expected in different areas that will affect the seismic analysis and design of new dams and the safety assessment of existing dams. In the assessment of future developments, the current ICOLD guidelines documented in several bulletins serve as benchmark. As these guidelines, which represent the state-of-the-practice, have not yet been implemented by all dam owners or dam safety authorities, the first steps in the future will be to follow the recommendations made in these guidelines. Moreover, the seismic safety standards used in some countries may be ahead of that of ICOLD and what is considered as new or future development may not be the case everywhere. It is also important to note that the future development does not mean new research results but new methods and guidelines that are suitable for practical application. Several problems in the seismic safety evaluation of dams have been discussed, which may be considered as the subjects where future developments are needed. Accordingly, the following developments may be expected in the future:

1. Seismic hazard evaluation of dam site: There are four aspects: (i) besides ground shaking the earthquake hazard includes faulting, mass movements and others; (ii) the dam engineer does not need real earthquake records as analysis input but models of the earthquake ground motion, (iii) for the safety check of dams spectrum-matched acceleration time histories of the safety evaluation earthquake are required, and (iv) improvements in ground motion prediction models, especially for ground motion parameters with very long return periods.

2. Seismic design criteria: Changes are related to (i) the seismic design of hydro-mechanical end electro-mechanical components of spillways and low-level outlets, (ii) the seismic load combinations, and (iii) the design criteria for dam cascades along rivers and very large reservoirs.

3. Seismic performance criteria: The general criteria may remain, but there is a need for low-level outlets.

4. Dynamic material properties: New material models are expected for embankment dam materials. The deformational characteristics of rockfill are required as input for advanced deformation analyses of embankment dams.

5. Methods of seismic analyses of dams: Nonlinear seismic analysis methods need further development. New types of embankment dams need reliable estimates of inelastic seismic deformations, e.g. asphalt core rockfill dams.

6. Seismic instrumentation of dams: Seismic instrumentation should be installed in all large dams.

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