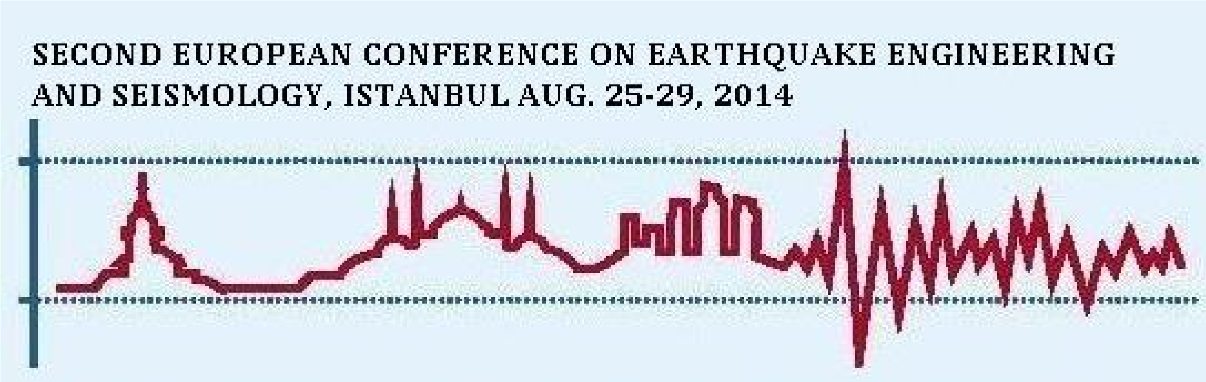

WHAT SEISMIC HAZARD INFORMATION THE DAM ENGINEERS NEED FROM SEISMOLOGISTS AND GEOLOGISTS?

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ABSTRACT

For large dam projects a site-specific seismic hazard analysis is usually recommended. These analyses are carried out by seismologists. It is important that the dam engineer, who is the end user of results of seismic hazard analyses, clearly specifies what he needs as the seismologists are not dam engineers and are not familiar with the safety concepts used in dam engineering and the seismic performance criteria for the different dam types, i.e. concrete arch dams, gravity dams, buttress dams, rockfill dams, concrete face rockfill dams and so on. Today large dams and the safety-relevant elements used for controlling the reservoir after a strong earthquake must be able to withstand the ground motions of the safety evaluation earthquake (SEE). The SEE ground motion parameters can be determined either by a probabilistic seismic hazard analysis or a deterministic analysis in which worst-case earthquake scenarios are considered. During the SEE inelastic deformations may occur in a dam, therefore, the seismic analysis has to be carried out in the time domain. In general seismologists provide response spectra or uniform hazard spectra, but acceleration time histories are needed for large dams. Moreover, inelastic deformations and damage mechanisms in dams depend on the duration of strong ground shaking and also the effects of aftershocks have to be accounted for by the dam engineer. Furthermore, earthquakes create multiple seismic hazards for dams such as ground shaking, fault movements, mass movements and reservoir-triggered seismicity (RTS) may also have to be considered. The ground motions needed by the dam engineer are not real earthquake ground motions but models of the ground motion, which allow the safe design of dams. In the paper the ground motion parameters needed by the dam engineers and the special features of design earthquake ground motions are discussed.

INTRODUCTION

Earthquakes have always played an important role in the design and safety of dams.

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 there are other components such as a power intake, penstock, powerhouse, device for control of environmental flow, fish ladder, desilting basins, slopes of cuts, switchyard, transmission lines, electro-mechanical equipment, etc.

All these structures and components must be able to withstand earthquake actions. Depending on the importance of these elements they can be classified as follows:

(i) Dam body (concrete or fill dams) and safety-relevant elements (spillways and bottom outlets and related gates and electro-mechanical equipment and power supply, etc.).

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(ii) Appurtenant structures (office and storage buildings, powerhouse, switchyard, intake structures, electro-mechanical equipment etc.).

(iii) Temporary structures (river diversion structures including diversion tunnels, intake and outlet structures, coffer dams) and critical construction stages.

Different seismic design and performance criteria apply for these structures as discussed in ICOLD Bulletin 148 (ICOLD, 2014).

In the subsequent discussion the focus is on item (i) as these structures must be able to withstand the 'worst' earthquake action to be expected at the dam site. The 'worst' earthquake action is usually called maximum credible earthquake (MCE) ground motion. The MCE is an event, whose definition may be difficult especially in regions where the seismic activity of faults is unknown or where fault ruptures do not reach the surface etc. However, in this paper it is assumed that the worst-case earthquake scenarios for a dam site are known in terms of location at a specific fault, focal depth, maximum magnitude, maximum fault movement, source mechanism. The MCE concept has the advantage that a dam, which can withstand the effects of the MCE, is safe against earthquakes because no stronger earthquakes are possible. As there are uncertainties in the definition of the MCE this simple MCE concept, which can be explained more easily to the public than the results of any probabilistic analysis, is not that simple.

The main objectives of this paper are to discuss the results of seismic hazard analysis a dam engineer needs from the seismologists and geologists.

MAIN SEISMIC HAZARDS FOR LARGE DAM PROJECTS

The earthquake hazard is a multi-hazard, which includes the following main hazards for a large dam project (Wieland, 2014):

(i) ground shaking,

(ii) movements along faults or discontinuities in the footprint of the dam, and

(iii) mass movements into the reservoir causing impulse waves and rockfalls damaging transmission lines, blocking access roads, etc.

Ground shaking is usually considered as the main seismic hazard. However, movements in the footprint of a concrete dam are more critical than ground shaking, as any such movements would, for example, cause a complicated crack pattern in highly statically indeterminate arch dams, which cannot be predicted reliably by numerical models. The dynamic behaviour of the dam will become very complex as cracking in the dam due to foundation movement and ground shaking will occur at the same time. Therefore the possibility of foundation movements has to be studied carefully. Even if no seismogenic fault is crossing the dam foundation, a strong earthquake at a nearby fault can cause movements along discontinuities in the footprint of a dam. These discontinuities are faults, shear zones, fissures, joints, and bedding planes. Such movements are hard to estimate as they depend on the site conditions, the distance from the seismically active fault and its maximum surface movement. Some faults may also splay near the surface and reactivate discontinuities.

Conservatively designed earth core rockfill dams can cope with such movements, whereas arch dams will be very vulnerable. Therefore, in the case of doubt regarding the possibility of fault movements a conservatively designed earth core rockfill dam would be the appropriate solution (ICOLD, 1999; ICOLD, 2001).

Mass movements into the reservoir would create impulse waves, which may overtop the dam crest. Here concrete dams would be more suitable to resist limited overtopping than embankment dams. However, by an ample freeboard and/or an upstream parapet or wave wall this overtopping hazard can be eliminated.

Moreover, mass movements in the reservoir region will increase the sediment volume in the reservoir and may block the bottom outlet. But this will happen in the months or years after the earthquake and there is time for remedial action.

Rockfalls in mountainous regions could damage transmission towers, which would lead to the automatic shut-down of the power plant. However, more critical would be rockfall damage of gate room structures, equipment, emergency power generators, control units etc. needed for the operation of the gates of spillways and bottom outlets. These gates have to be operable after a strong earthquake as it must be possible to control or lower the reservoir and to release a moderate flood after a strong earthquake. Again, if these gates are blocked this would lead to overtopping of the dam crest, which would be a much more serious safety problem for embankment dams than for concrete dams where limited overtopping may be accepted.

Therefore, it can be concluded that input will be needed from seismologists and geologists on (i) ground shaking, (ii) movements in the footprint of a dam (this is most important if a monolithic concrete dam is planned), and (iii) critical slopes in dam and reservoir region.

Usually, seismic hazard analyses are only concerned with the estimate of ground motion parameters such as peak ground acceleration (PGA) and response spectra.

The ground motion parameters can be determined by a probabilistic and/or deterministic seismic hazard analysis as discussed by Wieland (2012) and ICOLD Bulletin 148 (ICOLD, 2014). Accordingly the dam body and the safety-relevant elements must be able to withstand the ground motion of the safety evaluation (SEE) earthquake with a return period of 10,000 years (probabilistic analysis) or those from worst-case earthquake scenarios (deterministic analysis). In the probabilistic analysis the mean values of the ground motion parameters shall be used whereas in the deterministic analysis the mean plus one-sigma values. If both a probabilistic and deterministic analysis is done, which is recommended, then the maximum values of the ground motion parameters shall be used.

As in over 100 large storage dams reservoir-triggered seismicity (RTS) was observed (ICOLD, 2011), it is also necessary for the seismologist to address this hazard and to define possible scenarios although this is probably as difficult as earthquake prediction. RTS is not a dam safety problem, as it is designed for the worst ground motion at the site, but may affect buildings and infrastructure projects in the dam and reservoir region and frequent noise from moderate magnitude events may disturb people.

EARTHQUAKE ANALYSIS OF DAMS AND EARTHQUAKE INPUT

Under the SEE ground motion it is required that the dam can safely retain the reservoir and that after the earthquake the reservoir can be controlled, i.e. it must be possible to lower the reservoir and it must be possible to release a moderate flood. Therefore damage of the dam (inelastic deformations, cracks) is acceptable but its stability must be guaranteed and the gates of the spillway and bottom outlet must be operable after the earthquake.

As inelastic deformations are accepted and since it is not feasible to call for a fully elastic behaviour of the dam under extreme earthquakes, nonlinear dynamic stress, deformation and stability analyses have to be carried out.

These nonlinear dynamic safety analyses must be carried out in the time domain. Therefore, the earthquake input must be in form of acceleration time histories. Thus the ground motion parameters obtained from the usual seismic hazard analyses (uniform hazard spectra from probabilistic analyses or acceleration response spectra from deterministic analyses) cannot be used by the dam analysts They have to be processed further and 'converted' into acceleration time histories.

EARTHQUAKE LOAD MODELLING FOR DAM DESIGN

It has been and it still is standard practice in the design of buildings, infrastructure projects including large dams to use models of the different static and dynamic actions. These load models have little in common with real loads but the use of these load models have resulted in safe structures.

Dams were the first structures, which were designed against earthquakes worldwide starting from the mid-1930s. Even for dam projects where no information was available on the seismicity a seismic coefficient of 0.1 was used in conjunction with a pseudo-static analysis. Thus the earthquake action was represented by a single ground motion parameter. The seismic coefficient had little in common with today's PGA-value. This seismic design concept was used until the 1980s. Although, today, this concept is considered obsolete and even wrong, engineers would still like to use it because of its simplicity and try to establish correlations between the seismic coefficient and the PGA.

In 1989 ICOLD published the first version of the guideline 'Selecting Seismic Parameters for Large Dams' where it was specified that a dam must be able to withstand the MCE ground motion.

This guideline was updated and approved in 2010 (ICOLD, 2014). In this guideline recommendations on modelling of the earthquake ground shaking (acceleration time histories) for dam design are given which are discussed below.

It is recommended that several acceleration time histories be used to represent the SEE ground motion. Acceleration time histories must be specified for horizontal and vertical components and should preferably be represented by real accelerograms obtained for site conditions similar to those present at the dam site under consideration. But such records must often be supplemented by synthetic motions representing any earthquake size and seismotectonic environment. There exist several techniques for the generation of synthetic acceleration time histories.

For the acceleration time history models synthetic or recorded acceleration time histories can be used taking into account the following aspects (ICOLD, 2014):

(1) The three components of the spectrum-matched (synthetic) acceleration time histories must be statistically independent.
(2) The acceleration time histories of the horizontal earthquake components may be assumed to act in along-river and across-river directions. No modifications in the horizontal earthquake components are needed if they are applied to other directions, i.e. directivity and near-fault effects do not have to be taken into account.
(3) The duration of strong ground shaking shall be selected in such a way that aftershocks are also covered.
(4) In the case of dams, which are susceptible to damage processes which are governed by the duration of strong ground shaking such as, e.g., the build-up of pore pressures in fill dams or the sliding movement of Slopes or concrete blocks, earthquake records with long duration of strong ground shaking shall be used.
(5) For the safety check of a dam at least three different earthquakes shall be considered for the SEE ground motion.

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

It must also be taken into account that in the seismic analysis and design of dams a number of assumptions have to be made such as neglect of non-uniform ground motions, modelling of dynamic dam-foundation interaction, dynamic interaction with the reservoir, material properties and in particular structural damping of concrete dams, constitutive models etc. Therefore, the degree of accuracy of the seismic ground motion is not the prime concern in the seismic analysis and design as long as the acceleration records comply with the different aspects listed above.

This earthquake load model concept may be very disturbing to seismologists, who want to provide the most realistic acceleration records. But it is the dam engineer, who ultimately is responsible for the safety of a dam and not the scientists who provide the seismic input.

In order to get the proper input for the seismic analysis and design of the dam, it is necessary that the dam engineers writes the specifications for the type of results required from a seismic hazard study and the ultimate result needed are different sets of acceleration time histories for the SEE.

If the seismic hazard analyst will not provide these acceleration time histories, they have to be generated by the dam analyst. Therefore, it is very important that the seismic hazard analysts understands that the seismic design is based on earthquake load models and not real earthquake records. The latter would mainly be needed if reanalysis of a dam has to be carried out which was subjected to a specific earthquake, but this is not the seismic design and safety evaluation case.

Besides acceleration time histories also displacement time histories may be needed for safety-relevant underground structures.

It has to be realized that properly maintained dams have a very long service life. Therefore, it has to be assumed that during their lifespan several seismic safety evaluations of a dam will be carried out. The main reasons for such reassessments are:

- New information on seismic hazard and/or seismotectonics is available;
- New features of ground motion are introduced such as non-uniform ground motion, directivity effects, near fault features, etc.
- Dam has been subjected to strong earthquake shaking;
- New seismic design criteria are introduced;

- New seismic performance criteria are introduced;
- New dynamic methods of analysis are introduced;
- Seismic vulnerability of dam has increased;
- Seismic risk has increased, etc.

Because of the long service life of dams, the temporal variation of the seismic hazard is not taken into account. For example, it could be argued that after a major earthquake in a project region the tectonic stresses have been reduced and thus the likelihood of a similar earthquake in the near future is reduced. Such features shall not be accounted for in the dam industry.

CONCLUSIONS

For the seismic analysis, design and safety assessment the dam engineer needs the following information from the seismologists and geologists:

(1) Are there active faults or discontinuities in the footprint of the dam, which could be reactivated during strong earthquakes and what is the maximum possible movement?
(2) What are the worst-case earthquake scenarios for the dam site (fault, location, focal depth, source mechanism, upper bound magnitude, maximum fault movement)?
(3) Are there any slopes at the dam site and in the reservoir region, which could fail or move during strong earthquakes?
(4) For the inelastic seismic analysis of the dam acceleration time histories are required as input.
(5) The dam engineer must clearly specify what results are required from a seismic hazard analysis. For example, unit hazard spectra obtained from a probabilistic seismic hazard analysis cannot be used as input for a nonlinear dynamic analysis and, therefore, need further processing.
(6) The acceleration time histories of the safety evaluation earthquake needed for the dam design represent load models, which have little in common with real acceleration records.
(7) The duration of strong ground shaking of the spectrum-matched acceleration time histories must account for aftershocks and the critical seismic failure mechanisms of the dam (extended durations shall be selected).
(8) The different acceleration components shall be statistically independent, directivity and near-fault effects do not have to be considered.
(9) During the lifespan of a dam several seismic safety assessments will be needed if new information on the seismic hazard becomes available, new design and safety criteria are introduced and when the seismic risk increases due to the development in the downstream valley, etc.

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