CRITERIA FOR THE SELECTION OF DAM TYPES IN AREAS OF HIGH SEISMICITY

M. Wieland[1]

1. Chairman, ICOLD Committee on Seismic Aspects of Dam Design, Poyry Switzerland Ltd., Herostrasse 12, CH-8048 Zurich, Switzerland, martin.wieland@poyry.com

PRESENTER: M. WIELAND

ABSTRACT

Strong earthquakes are multi-hazard events, which can affect large dams in different ways. The main hazards are: ground shaking; active or potentially active faults, discontinuities in the footprint of dams, which can be activated during strong nearby earthquakes; active faults in the reservoir; mass movements into the reservoir and at dam site; and other project-specific and site-specific hazards. In the comparison of the earthquake resistance of different dams the focus has always been ground shaking. Concrete face rockfill dams, arch dams and others have been declared the best by their designers. But very few have been exposed to strong earthquakes. A qualitative comparison of different dam types is made.

1. INTRODUCTION

Very few large dams, designed according to the current state-of-practice (ICOLD, 2016), have been subjected to the effects caused by the safety evaluation earthquake (SEE). Therefore, the knowledge on the seismic vulnerability of dams is still limited.

We also have to realize that strong earthquakes are multi-hazard events, which can affect large dams in different ways. The main hazards are: ground shaking; active or potentially active faults, discontinuities in the footprint of dams, which can be activated during strong nearby earthquakes; active faults in the reservoir; mass movements into the reservoir and at dam site; and other project-specific and site-specific hazards. In the comparison of the earthquake resistance of different dams the focus has always been on ground shaking. Accordingly, concrete face rockfill dams, arch dams and other dams have been declared the best by the designers, favouring these dam types. But very few have been exposed to strong earthquakes and, therefore their seismic weaknesses are not yet known.

However, it is known that fault movements are more critical for concrete dams than for earth core rockfill dams (ECRDs). Therefore in tectonically active regions where movements along discontinuities in the dam footprint cannot be excluded, ECRDs are the preferred solutions (ICOLD, 1998).

Also the often heard argument that no modern dams have been destroyed during strong earthquakes cannot be accepted as a reason that the dams owned by a particular owner are safe against earthquakes as an observation period of say 100 years is by far too short in view of the recurrence interval of the SEE of 10,000 years for large storage dams.

To judge if a dam is safe needs a more thorough analysis of its seismic vulnerability. As all dams are prototypes, located in unique environments, therefore probabilistic dam safety concepts would include huge uncertainties and cannot be recommended.

The following items must be considered in the seismic safety assessment of dams (Wieland, 2014):

(1) Seismic hazard at the dam site,

(2) Seismic vulnerability of the dam (dam type, age, condition of the dam, etc.),

(3) Material properties under seismic action and damping parameters,

(4) Dynamic response of dam (stress and deformation analyses, stability analyses), and

(5) Comparison of calculated seismic response with seismic performance criteria derived from the analysis of possible failure modes, i.e. allowable deformations, crack width, stresses, sliding movements, pore pressure build-up, etc.

Such safety assessments are needed for all dams including dams, which either have not been designed against earthquakes or have been designed using outdated seismic design criteria, where (i) the earthquake hazard is represented by a seismic coefficient, and (ii) simplistic seismic analyses such as the pseudo-static analysis method have been used. However, the present paper is concerned with the seismic safety aspects of new dams.

It must be pointed out that the assumption that a dam, which was safe at the time of construction remains safe forever, is a misconception, as during the long life of a dam several seismic safety checks will be required. The main reasons for such safety checks are:

(1) New information on seismic hazard and/or seismotectonics is available;

(2) Dam has been subjected to strong earthquake shaking;

(3) New seismic design criteria are introduced;

(4) New seismic performance criteria are introduced;

(5) New methods of seismic analysis are introduced;

(6) Seismic vulnerability of dam has increased (e.g., due to ageing);

(7) Seismic risk has increased (e.g., due to population growth and economic development in the downstream flood plain), etc.

There has been significant development in the methods for seismic hazard assessment in recent years and ICOLD's seismic design criteria (ICOLD, 2016) have been updated, specifying explicitly that the safety-relevant elements, i.e. spillway gates and bottom outlets, which are required for operating the reservoir after a strong earthquake, must be operable.

Also after strong earthquakes that have damaged dams and hydropower projects, a reassessment of (i) the seismic hazard, (ii) the seismic design criteria, (iii) the seismic design concept and the seismic safety of the dam, and (iv) safety-relevant elements, is necessary.

Due to the unique nature of each site and the type and size of dams, it is necessary to calculate the dynamic response of the dam conservatively. This does not mean that the most sophisticated numerical analysis models should be used. Basically the numerical models shall be suitable for checking specific failure modes. Moreover, the results should be on the safe side. For design purposes, models of the acceleration time histories are used by dam engineers. These time history models have very little in common with recorded accelerograms. This is a fact that can hardly be accepted by earth scientists. But earth scientists are not dam engineers and vice versa. But the concept of load models is a standard practice used in the safe design of civil structures and the same is true for the seismic design of storage dams. Therefore, in the seismic design of a dam it is the dam engineer (and not the 'seismologist'), who interprets the results of the seismic analyses and makes adjustments in the dam design, if needed.

As can be noted from this discussion, there are many factors to be considered in the seismic design and safety assessment of dams, which makes it very difficult to arrive at a clear answer of the safest dam type. In the subsequent sections different dam types are discussed.

2. SAFETY ASPECTS

The main goals of every dam safety concept are the minimisation of all risks, and the mastering of the remaining risks in the best possible way. To reach these goals a comprehensive safety concept is used for large storage dams, which includes the following key elements (Wieland and Mueller, 2009):

(1) Structural safety (main elements: geologic, hydraulic and seismic design criteria (design criteria and methods of analysis may have to be updated when new data are available or new guidelines, regulations or codes are introduced));

(2) Dam safety monitoring (main elements: dam instrumentation, periodic safety assessments by dam experts, etc.);

(3) Operational safety (main elements: reliable rule curves for reservoir operation under normal and extraordinary (hydrological) conditions, training of personnel, dam maintenance, sediment flushing, engineering back-up. The most important element for a long service life is maintenance of all structures and components);

(4) Emergency planning (main elements: emergency action plans, inundation maps, water alarm systems, evacuation plans, etc.).

Therefore, as long as the proper implementation of these safety issues can be guaranteed according to this integral safety concept, a dam can be considered as safe.

In the design of large dams all possible hazards affecting the project must be considered: (i) hazards from the natural environment, (ii) structural or project-specific hazards, and (iii) man-made hazards. For mastering the resulting risks the following protective measures can be taken for existing dams:

(1) Rehabilitation,

(2) Partial reservoir drawdown,

(3) Full reservoir drawdown,

(4) Evacuation, and

(5) Post-event evacuation.

As strong earthquakes cannot be predicted, only post-event evacuation is possible.

In the safety discussion of structures it is always mentioned by risk analysts that no structure is absolutely safe when they are referring to very low probability of failure. Such statements are meaningless if all hazards have to be considered for a dam project as it is clear that any type of structure can be destroyed by man irrespective of the annual probability of failure, which cannot be calculated for the most severe man-made hazards such as terrorism, sabotage and war. Therefore, probabilistic safety analyses exclude such hazards and thus are of little use. However, probabilistic analyses are suitable for the definition of the hazards from the natural environment.

Moreover, as dams are prototypes, it is not really possible to calculate the probability of failure of the dam body, but this may be easier for the safety-relevant hydro-mechanical equipment.

However, if we focus on the seismic hazard and in particular on the effect of ground shaking then the uncertainties in the risk analysis can be narrowed down in comparison to the case where all possible hazards have to be taken into account. But it is still a very difficult task and we cannot rely on such results. Therefore, rather than trying to reduce the risk of failure, it is more effective to try to minimise the consequences of a dam failure. Loss of live can be minimised by water alarm systems. For example, acoustic alarm systems have been installed for 65 dams and dam cascades in Switzerland. The first ones are about 60 years old. Fortunately they never had to be used. But annual rehearsals are being carried out involving the main decision makers in an emergency situation.

In conclusion, dam safety is very complex and cannot be discussed in greater depth in this paper. However, the reader can note that the discussion of the safest dam type during an earthquake is not that straightforward. Basically every dam type can be made earthquake safe when the local conditions are suitable, but every dam can also be destroyed by humans.

Finally we must keep in mind that the main risk factor in storage dams is the water stored behind the dam. If there is no water in the reservoir then the people living downstream of a dam have nothing to worry and any seismic damage of the dam will be the concern of the dam owner only. However, the critical case is when a catastrophic release of water from the reservoir is possible, i.e. when the reservoir is full. Therefore in the safety discussion we have to focus mainly on the dam with full reservoir.

3. SEISMIC FAILURE MODES

In the discussion of the earthquake safety of dams, we must look into the main failure modes of the different dam types.

In concrete dams only very few cracks are expected to occur along block joints of arch dams and mainly horizontal lift joints of all types of concrete dams (Malla and Wieland, 2003). The formation of cracks (in tension) will protect the other parts of the mass concrete from high dynamic tensile stresses. Therefore, most of the seismic deformations will be along joints and cracks.

For concrete gravity dams and buttress dams the main failure modes due to ground shaking are as follows:

(1) Sliding of concrete block along discontinuities in foundation rock or along the dam-foundation contact (sliding in downstream direction).

(2) Local sliding stability of concrete blocks near the dam crest (sliding in downstream direction along lift joints).

For concrete arch and arch-gravity dams the main failure modes due to ground shaking are as follows:

(1) Global sliding of dam or different blocks along discontinuities in foundation rock or along the dam-foundation contact (sliding in downstream direction).

(2) Local sliding stability of concrete blocks near the dam crest (sliding in upstream direction along lift joint; due to the dam geometry, sliding movements are larger for empty reservoir than for full reservoir).

(3) Crushing of concrete in thin arch dams under high seismic compressive stresses in arch direction (spalling of concrete and loss of bearing capacity in arch direction).

For masonry gravity dams the main failure modes due to ground shaking are as follows:

(1) Global sliding of dam along discontinuities in foundation rock or along the dam-foundation contact (sliding in downstream direction).

(2) Local sliding stability of dam crest due to formation of cracks along mortar contact and core of the dam (no characteristic failure mode of masonry dams).

For RCC dams the failure modes are basically the same as for conventional mass concrete dams.

For embankment and earth core rockfill dams (ECRDs) the main failure modes due to ground shaking are as follows:

(1) Overtopping of dam crest due to seismic settlements and/or slope movements.

(2) Internal erosion due to damage of filter of ECRDs.

(3) Internal erosion along soil-concrete interfaces.

For concrete face rockfill dams (CFRDs) the main failure modes due to ground shaking are as follows:

(1) Overtopping of dam crest due to seismic settlements and/or slope movements.

(2) Excessive leakage and formation of seepage channel due to local failure of concrete face caused by curb failure and/or excessive deformations of rockfill with relatively low permeability, etc.

For asphalt core rockfill dams (CFRDs) the main failure modes due to ground shaking are as follows:

(1) Overtopping of dam crest due to seismic settlements and/or slope movements.

(2) Excessive leakage and formation of seepage channel due to local failure of thin asphalt core caused by excessive deformations of rockfill with relatively low permeability, etc.

For rockfill or embankment dams with upstream asphalt membrane or geotextile the main failure modes due to ground shaking are as follows:

(1) Overtopping of dam crest due to seismic settlements and/or slope movements.

(2) Excessive leakage and formation of seepage channel due to local failure of asphalt face or geotextile on rockfill with relatively low permeability etc.

The overtopping failure mode may also be caused by the malfunction of spillway gates and bottom outlets. The most vulnerable dams for overtopping are embankment dams. Limited overtopping of concrete dams can be accepted. To prevent this failure mode, either ungated spillways or emergency spillways (fuse plugs) or a combination of gated and ungated spillway openings can be provided in embankment dams.

4. SUITABILITY OF DIFFERENT DAM TYPES FOR MULTIPLE SEISMIC HAZARDS

In the subsequent part a qualitative ranking of the different dam types is given for the main seismic hazards, i.e. ground shaking, fault movements in the footprint of the dam, and mass movements. This ranking could be used to assess the seismic vulnerability of existing dams where not all aspects of the seismic hazard were taken into account. For new dams, the design can account for most seismic hazards, except fault movements in concrete dams as it is not known if slip joints will work as intended. The word suitability may also be considered as a synonym for the vulnerability in the subsequent sections.

For strong ground shaking, the suitability of dams is estimated as follows, assuming that they are well designed and built:

(1) Earth core rockfill dams: good

(2) Rockfill or embankment dams with upstream surface geotextile: good

(3) Concrete gravity, arch-gravity and arch dams: good

(4) Asphalt face rockfill or embankment dams: may be vulnerable to seismic deformations, acceptable for limited seismic deformations (suitable for areas of low to moderate seismicity)

(5) Concrete face rockfill dams: may be vulnerable to seismic deformations, acceptable for limited seismic deformations (suitable for areas of low to moderate seismicity)

(6) Asphalt core rockfill dams: thin cores may be vulnerable to seismic deformations (suitable for areas of low to moderate seismicity)

(7) Buttress dams: problematic (two buttress dams have already been damaged during strong earthquakes)

(8) Masonry dams: not recommended (masonry structures of all types have performed worst during past earthquakes).

For fault movements in the footprint of dams or discontinuities in the footprint of dams, which could be activated by nearby strong earthquakes, the suitability of dams is estimated as follows (Wieland et al., 2008a and 2008b):

(1) Earth core rockfill dams: good

(2) Rockfill or embankment dams with upstream surface geotextile: good

(3) Asphalt face rockfill or embankment dams: acceptable for limited deformations

(4) Concrete face rockfill dams: acceptable for limited deformations

(5) Asphalt core rockfill dams: problematic for dams with thin asphalt core

(6) Concrete gravity, arch-gravity and buttress dams: not recommended

(7) Arch dams and masonry dams: problematic (shall be avoided)

For earthquake-triggered mass movements (rockfalls) at the dam site in mountainous regions, the suitability of the different dam types is estimated as follows:

(1) Earth core rockfill dams with wide crest: good

(2) Asphalt core rockfill dams with wide crest: good

(3) Masonry and concrete gravity, arch-gravity dams with wide crest: good

(4) Concrete face rockfill dam (CFRD): consequences must be checked (damage of concrete face)

(5) Buttress dams: problematic

(6) Rockfill or embankment dam with upstream surface geotextile or asphalt face: problematic

(7) Thin arch dams: very vulnerable.

It has to be accepted today that during a strong earthquake such as the SEE, the dam body will experience inelastic deformations. Therefore, in the assessment of the suitability of dams, the engineer should also look into possible repair works. It is obvious that repairs can best be done when the reservoir level is below the damaged zone. For that purpose a low level outlet or bottom outlet of adequate discharge capacity would be very helpful as otherwise repair works would have to be done underwater with the help of divers. In Switzerland all large dams must have a bottom outlet.

For example, in view of possible repairs, the repair of the concrete face of a CFRD at low reservoir level is much easier than the repair of a damaged asphalt core of an asphalt core rockfill dam.

The seismic vulnerability of a dam at a particular site depends, on the one hand, on the design and, on the other hand, on the quality of the construction works. The importance of good construction shall not be underestimated by all means. A poorly constructed dam may fail already under a minor earthquake whereas a well-designed and well-constructed dam can behave very well even under an earthquake with a peak ground acceleration of 1 g.

Because of such wide scatter in seismic performance any dam type ranking has to be based on the assumption of proper design and construction.

In conclusion, for strong ground shaking concrete gravity, arch-gravity and arch dams, ECRDs and CFRDs can be designed and constructed equally safe if the local site conditions are suitable for these dam types. Therefore, the main factors for the selection of one of these dam types are economic ones.

For fault movements the best types of dams are ECRDs and rockfill dams with upstream geotextile. The least suited dams for such sites are concrete dams and in particular arch dams.

For mass movements (mainly rockfall in mountainous regions) concrete gravity and arch-gravity dams, ECRDs and asphalt core rockfill dams can be designed and constructed equally safe.

If all three above-mentioned seismic hazards have to be taken into account in a highly seismically active region, then a conservatively designed and well-constructed ECRD is the best solution.

5. MAIN FEATURES OF CONSERVATIVELY DESIGNED EARTH CORE ROCKFILL DAM

The main recommendations for the design and construction of embankment dams subject to severe earthquake shaking and foundation movements are as follows (ICOLD, 2001):

(1) 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.

(2) Flat slopes to reduce earthquake-induced deformations.

(3) Fill materials, which tend to build up significant pore water pressures during strong shaking must not be used.

(4) All zones of the embankment must be thoroughly compacted to prevent excessive settlement during an earthquake.

(5) 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.

(6) Impervious core made of ductile material with a high failure strain to minimize the propagation of the rupture zone; prevention of internal erosion if core is cracked.

(7) Filters must be provided on fractured foundation rock to preclude piping of embankment into the foundation.

(8) Wide filter and drain zones must be used (about 50% of the fine sand filter shall still be available after faulting and earthquake-induced slip movements of slopes.

(9) The upstream and/or downstream transition zones should be self-healing, and of such gradation as to also heal cracking within the core.

(10) 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.

(11) 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.

Figure 1. View of core, filter and transition zones in ECRD located in a narrow canyon with multiple discontinuities in the footprint of the dam. The fine sand filter is flared towards the abutment

The main concern of any embankment dam with impervious core is the erosion resistance of the core material. The filter and transition zones provide the first line of defence against earthquake-induced concentrated leaks through the dam.

An example of an ECRD located in a narrow canyon with multiple discontinuities in the footprint of the dam, which could move during a strong nearby earthquake is shown in Fig. 1.

The main design features are a wide fine sand filter, coarse sand filter and coarse transition zone at both the upstream face of the core. At the downstream face the thickness of the fine sand filter is widened towards the abutment and at the contact of the core with the abutment an up to 5 m wide plastic clay zone is provided to facilitate settlement of the core and to prevent arching and cracking.

In Fig. 2 the downstream face of the dam is shown. The peak ground acceleration of the SEE is 0.74 g for the horizontal earthquake component on the rock surface and maximum fault movements considered in the design are 2 m.

Figure 2. Downstream view of the ongoing construction works of the Rudbar Lorestan earth core rockfill dam, which is located in an area of high rockfall hazard and strong earthquakes. On the left bank the two spillway tunnel portals and the outlet of the diversion tunnel are visible.

6. CONCLUSIONS

The main conclusions of this qualitative assessment of the suitability and selection of dam types in highly seismic areas are as follows (Note: this assessment is that of the author):

(1) Earth core rockfill dams (ECRDs) are the most suitable and safest dam type in tectonically active regions with multiple seismic hazards comprising ground shaking, fault movements and rockfalls.

(2) For strong ground shaking the most suitable dams are concrete gravity, arch-gravity and arch dams, ECRDs and CFRDs. They can be designed and constructed equally safe if the local site conditions are suitable for these dam types.

(3) For fault movements the best types of dams are ECRDs and rockfill dams with upstream geotextile. The least suited dams for such sites are concrete dams and in particular arch dams.

(4) For rockfall hazard concrete gravity and arch-gravity dams, ECRDs and asphalt core rockfill dams can be designed and constructed equally safe.

(5) In tectonically active regions, where any fault could become potentially active, if not proven otherwise, it would be prudent to select ECRDs.

(6) Ungated spillways and bottom outlets would be additional seismic safety features of ECRDs.

7. REFERENCES

ICOLD (1998): Neotectonics and Dams, Bulletin 112, Committee on Seismic Aspects of Dam Design, ICOLD, Paris, France.

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

ICOLD (2016): Selecting Seismic Parameters for Large Dams, Guidelines, Bulletin 148, Committee on Seismic Aspects of Dam Design, ICOLD, Paris, France (in press).

Malla, S. and Wieland, M. (2003): Simple model for safety assessment of cracked concrete dams subjected to strong ground shaking. Proc. 21st Int. Congress on Large Dams, ICOLD, Montreal, Canada, June 2003

Wieland, M. (2014): Earthquake Vulnerability of Dams and Criteria for Selection of Dams in Seismic Regions, Proc. International Symposium on Dams in a Global Environmental Challenges, ICOLD Annual Meeting, Bali, Indonesia, June 1-6, 2014

Wieland, M., Brenner, R.P. and A. Bozovic, A. (2008a): Potentially active faults in the foundations of large dams part I: Vulnerability of dams to seismic movements in dam foundation, Special Session S13, Proc. 14th World Conf. on Earthquake Engineering, Beijing, China, Oct. 2008

Wieland, M., Brenner, R.P. and A. Bozovic, A. (2008b): Potentially active faults in the foundations of large dams part II: Design aspects of dams to resist fault movements, Special Session S13, Proc. 14th World Conf. on Earthquake Engineering, Beijing, China, Oct. 2008

Wieland, M. and Mueller, R. (2009): Dam Safety, Emergency Action Plans, and Water Alarm Systems”, Int. Journal Water Power and Dam Construction, January.