Are higher seismic safety standards required for dams forming dam cascades along rivers?

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ABSTRACT:

Along major rivers, several large dams have been built or are being built, forming dam or run-of-river power plant cascades. The cascades could consist of concrete or embankment dams or run-of-river power plants depending on the longitudinal profile of the river. As the failure of any storage dam in a cascade may cause overtopping and/or failure of the downstream dams, the probability of catastrophic release of water from a dam cascade is larger than that of the failure of a single dam. The paper is concerned with the probabilistic and deterministic seismic safety aspects of dam cascades. At present, in the design of large dams extreme floods and the worst earthquake ground motion at a dam site have to be taken into account. Due to the difficulties in determining the probability of failure of a dam subjected to earthquake action, it is proposed to determine the safety criteria of dams forming dam cascades by focusing on the consequences of a cascade failure rather than on the probability of failure of individual dams. As all dams are prototypes, and since only one large embankment dam has failed during a strong earthquake, statistical analyses of seismic failure of dams are meaningless.

1 INTRODUCTION

For hydropower generation, dams or run-of-river power plants have been constructed or are being built along several rivers, forming dam cascades. The dams are concrete or embankment dams and the run-of-river power plants are concrete structures or mixed concrete-embankment dam structures. Depending on the longitudinal profile of the river, high head dams are located along the upper reach, whereas low head run-of-river power plants are located along the middle and lower reaches of rivers. As an example, Figure 1 shows a cascade with run-of-river power plants along the Rhone River in France and in Figure 2 the planned and constructed hydropower plants along the Mekong River in China, Laos and Cambodia are depicted.

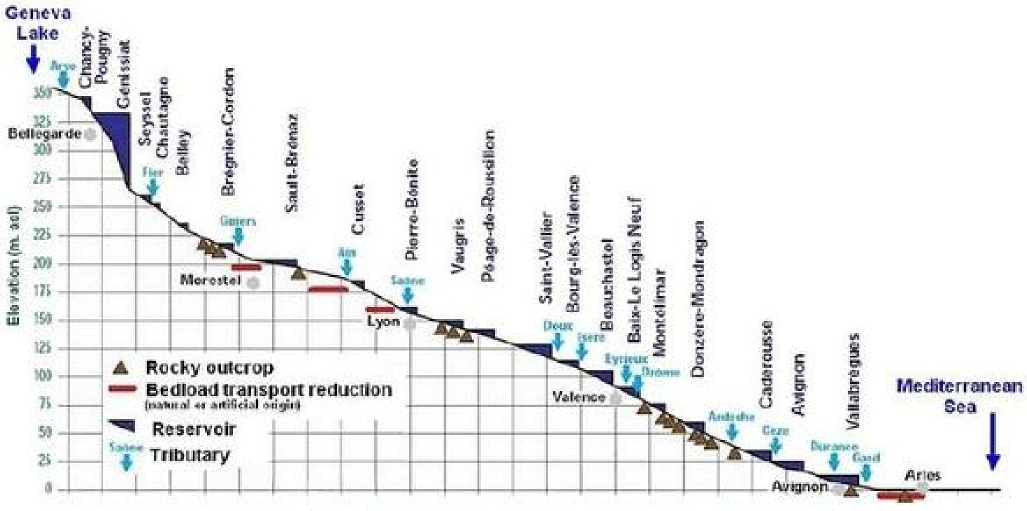

Figure 1. Longitudinal profile of the French Rhone River with cascade of run-of-river power plants (Peteuil 2012)

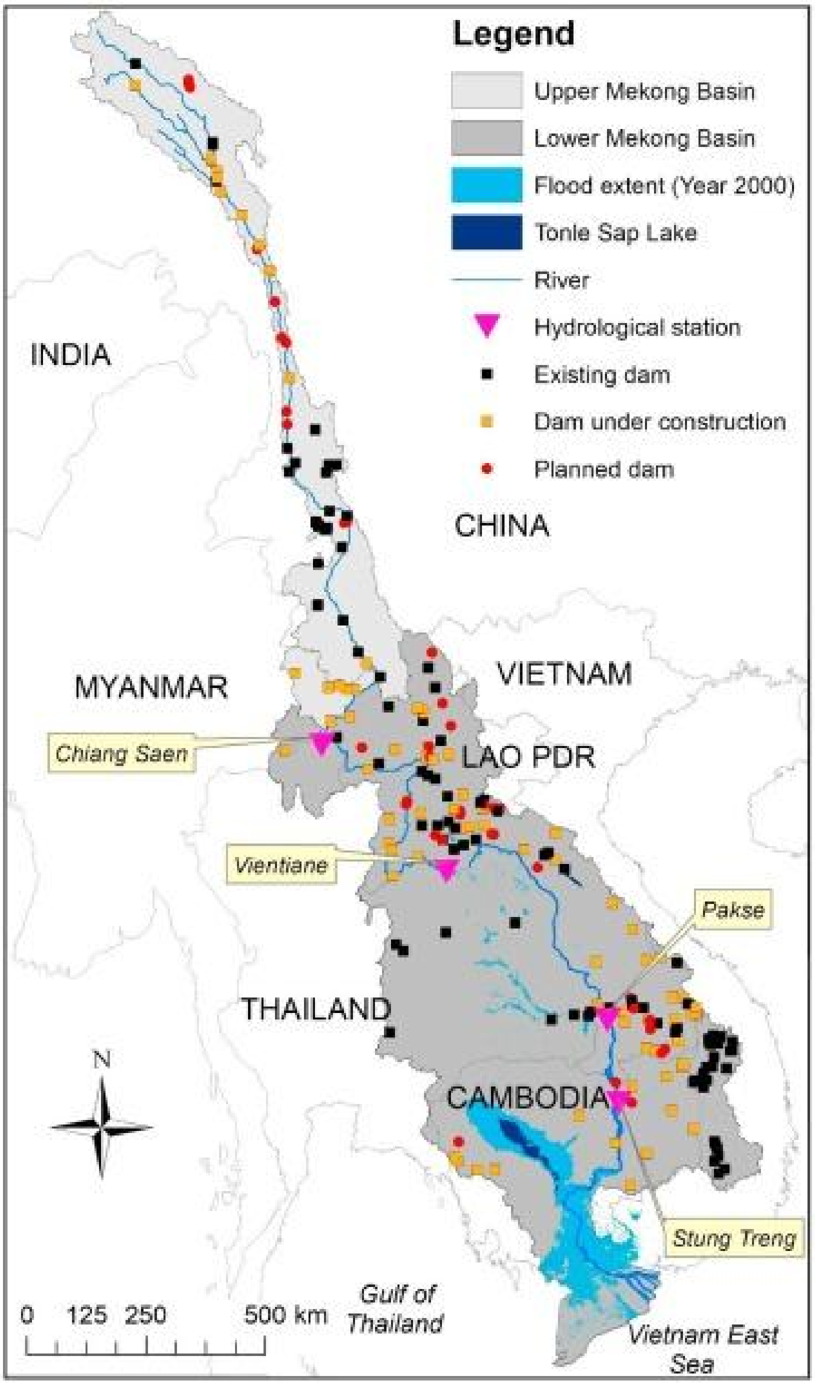

Figure 2. Plan of dam cascades: Dams built or planned along the Mekong River and tributaries (several dams along the upper and middle reaches of the Mekong are forming dam cascades, dam structures in middle and lower reaches form run-of-river power plant cascades)

As the failure of any storage dam in a cascade may cause overtopping and/or failure of the downstream dams, the probability of a catastrophic release of water from a dam cascade is larger than that of the failure of a single dam, calling for higher safety standards for dams in dam cascades. There are several hazards from the natural and man-made environment (Wieland, 2016) that may cause the failure of a dam. However, in this paper the focus is on the seismic hazard and the seismic safety aspects of dam cascades. Strong earthquakes may affect several power plants of a dam cascade at the same time, whereas the other hazards only affect individual projects more or less in a random way or may affect dams with some time delay as in the case of floods. Therefore, the seismic hazard is the most challenging one not only for dams but also for dam cascades located in seismic regions.

2 SEISMIC SAFETY ASPECTS OF DAM CASCADES

The seismic design and safety criteria for large dams are given in the ICOLD Bulletin 148 on the “Selection of Seismic Parameters for Large Dams” (ICOLD 2016), where, regarding the consequences of dam failure, three dam categories are distinguished and for each of them seismic design criteria are given. However, these consequence categories or risk classifications of dam projects are not defined explicitly in this ICOLD bulletin. The risk classification of dams, which may differ from country to country or even among different dam owners, is a key issue, as the design criteria depend on this classification. In general, the main parameters of the risk classification are the dam height and the reservoir volume. Other parameters may also be included in refined risk assessments.

As the failure of any dam in a dam cascade may cause overtopping or failure of the downstream dams and since the probability of failure of any dam of a cascade is larger than that of a single dam, the question arises, whether dams of a dam cascade need higher safety standards than single dams. The following items must be taken into account:

(i) If concrete dams are overtopped by a flood wave, it is likely that they will not fail. For example, during the 2008 Wenchuan earthquake in China, several run-of-river power plants (concrete structures) were overtopped, as the spillway gates could not be opened after the power plant was shut down (Figure 3). However, the overtopping depth was much smaller than in the case of a flood wave caused by the upstream failure of a dam. In the case of the 1963 rockslide into the Vajont reservoir, the depth of the flood wave overtopping the crest of the slender arch dam was of the order of 100 m, but the dam suffered only minor damage at the crest.

Figure 3. Overtopping of Taipingyi run-of-river power plant after the 2008 Wenchuan earthquake in China

(ii) If an embankment dam is overtopped by a flood wave then it must be expected that the dam fails and the stored water is released. Thus, in a dam cascade, the flood wave will be increased if there are embankment dams located downstream of a failed dam. It should be added that mixed concrete and embankment dams will experience similar failure modes due to overtopping as embankment dams.

(iii) Strong earthquakes may affect several dams of a dam cascade at the same time. However, the region with strongest ground shaking is limited and depends on the seismotectonic conditions. Therefore, as the distance between dams along rivers may be tens of kilometers, only very few dams will experience strong ground shaking. Thus, the level of ground shaking will be different at each dam site and the degree of damage and the probability of failure depend on the seismic vulnerability of a dam.

As large dams with a large damage potential are designed for the worst ground motion at a dam site, well designed and constructed dams should not fail at all during earthquakes, i.e. the dams of a dam cascade are safe and there is no need for stricter safety criteria. The situation may be different when some of the dams have been designed for lower seismic safety standards than the other dams. In this case, it would be necessary that all dams of a dam cascade are designed for the strongest ground shaking to be expected at all dam sites.

This deterministic safety scenario is a theoretical one, as in reality the dam designer and contractor are faced with different types of uncertainty. The main uncertainties are as follows:

(i) the seismic hazard and the earthquake ground motion,

(ii) the material properties and material models, and

(iii) the assumptions made in the seismic analysis of the dam with dynamic interaction with the foundation and the reservoir, seismic wave radiation and others.

We can account for the uncertainties in material properties and material models by sensitivity analyses, in which the most unfavorable properties of different material models are considered. Similarly, the uncertainties in the results of dynamic analyses can be assessed, by analyzing dam-reservoir-foundation models that give conservative results. In the case of the seismic ground motion, obtained from a site-specific seismic hazard analysis, we can calculate the seismic failure limit of the dam by analyzing the dam for ground motion levels exceeding the ground motion of the safety evaluation earthquake. With this approach, we can determine the seismic safety reserves of a dam. For example, if we can show that a dam is safe for a ground motion with a peak ground acceleration of 1.0 g, we are not concerned about the accuracy and uncertainties in the seismic ground motion where a peak ground acceleration of 0.3 g is expected. If in the dam design the conceptual guidelines given in ICOLD Bulletin 120 (ICOLD 2001) are followed, then by using the aforementioned approaches for dealing with uncertainties, the seismic safety of a dam can be confirmed, even in seismic regions. It is obvious that in areas of low to moderate seismicity, where the seismic load combination may not be the governing one, this conservative analysis approach is also applicable. However, for the assessment of the seismic safety of existing dams more advanced seismic analyses may be required. This also applies to new types of dam (e.g. concrete face rockfill dams, asphalt core rockfill dams, hardfill dams, etc.) and dams in regions of high seismicity. If, in the seismic analysis, conservative assumptions are made and too simplified analysis models are used, a seismic overdesign of the project might result or the safety of an existing dam cannot be verified.

Several papers have been written by the author in which various seismic analyses and safety aspects of large dams (Wieland 2018a: Wieland 2014), seismic design criteria and load combinations (Wieland 2019), modelling of earthquake ground shaking (Wieland 2018b), effects of aftershocks and multiple earthquakes (Wieland and Ahlehagh 2019) are discussed that are compatible with the ICOLD Bulletin 148 (ICOLD 2016).

Even if deterministic material parameters and conservative numerical analysis models are used, uncertainties remain for the seismic input when modern attenuation laws are used that include uncertainties. According to ICOLD (2016) 84-percentile values of the ground motion parameters are recommended in deterministic worst-case earthquake scenarios. In conclusion, even in a fully deterministic earthquake analysis, uncertainties in the seismic input and an “unknown” probability of seismic failure of a dam will remain.

How do we cope with the resulting uncertainties in dam safety? A reassessment of the seismic safety of dams will be required that includes primarily a review of the seismic hazard, the seismic design and the performance criteria. A dam may also move into a higher risk or consequence category, due to higher safety standards or increased risk in the downstream area.

In the probabilistic approach, the safety of a dam cascade is determined based on the probability of failure of dams subjected to earthquake ground motion. For simplicity, we consider the conditional probability of failure of a dam cascade subjected to the safety evaluation earthquake (SEE) ground motion, which according to ICOLD (2016) has a return period of 10,000 years for dams with a large damage potential. If we consider a dam cascade with "n" dams of the same type and the same seismic failure probability, p_f, and assume that all dams are subjected to the same ground motion, then the probability of failure of the cascade is $p_{fcas} = n\ p_f$. This value is much larger than that of the failure of a single dam. For the total annual probability of failure of the dam cascade, the contributions of the earthquake ground motions with different return periods and different frequencies of exceedance has to be added.

Standard probabilistic analysis methods may be used to compute the annual probability of failure of the cascade for this extreme failure scenario. As earthquake ground shaking is different at each dam site, the probability of failure of each dam will be different when subjected to a specific earthquake. Thus, the probability of failure of a dam cascade will be significantly less than n pf, as discussed in the above example.

The main problem with the probabilistic approach is that it is very difficult – or practically impossible – to determine the probability of failure of dams as all of them are unique. In the probabilistic safety analysis of nuclear facilities and other structures so-called fragility curves are used, in which the probability of failure is given as a function of the peak ground acceleration or another ground motion parameter. This is an obsolete approach and cannot be used for dams because of the following reasons:

(i) It is not possible to characterize the earthquake ground motion by a single seismic parameter. Even the description of the earthquake ground motion by an acceleration response spectrum is not sufficient as most damage mechanisms in dams (and other structures) depend strongly on the duration of strong ground shaking.

(ii) The definition of the failure limit of dams is difficult. The ultimate failure scenario is the uncontrolled catastrophic release of the water from the reservoir. There are different seismic failure modes that have to be considered.

(iii) The calculation of the seismic vulnerability of dams is still a great challenge. Analysis models that consider only a single ground motion parameter are too simplistic.

All dams are prototypes, therefore statistical analyses of dam incidents are not feasible. Moreover, only a single large dam has actually failed where the reservoir was released and people have been killed.

Although the earthquake hazard is described in a probabilistic format, it is difficult to determine the probability of failure of a dam subjected to earthquake action. The scatter in the results of dynamic analyses will be very large and almost meaningless for sound practical applications. Therefore, we propose determining the safety requirements of dams of dam cascades by focusing on the consequences of a cascade failure and to ignore the probability of failure of individual dams and dam cascades.

3 CONSEQUENCES OF FAILURE OF DAMS OF DAM CASCADES

A strong earthquake may affect all dams of a dam cascade at the same time, but the ground motion will be different in every site. The weakest dam will fail first. As shown in Figure 4, poorly designed and constructed dams will fail under moderate earthquakes, whereas well-designed and constructed dams can withstand very strong ground shaking.

If a dam fails during an earthquake, the dams located downstream of the failed dam may also fail due the flood wave created by the failure of the first dam.

The safety of a dam cascade is similar to the safety of a chain, where the safety is governed by the weakest element. Therefore, the seismic safety of all dams of a dam cascade should be determined in order to identify the weakest dams. Rather than trying to calculate the probability of failure of each dam of a dam cascade for the worst earthquake scenario of each dam, it is more practical to determine the seismic safety of a dam, using checklists, which include the following factors:

(i) type of dam,

(ii) construction materials,

(iii) age of dam and ageing effects,

(iv) initial seismic design criteria,

(v) results of seismic safety re-evaluations,

(vi) site-specific seismic hazard assessment, which includes ground shaking, faults or discontinuities in the footprint of the dam that could move during strong earthquakes, rockfalls or landslides at the dam site and the reservoir, etc.,

(vii) safety of spillway,

(viii) availability of low-level outlets (bottom outlet) and their seismic safety, etc.

Figure 4. Failure of Sharredushk embankment dam in Albania due to a magnitude 4.1 earthquake in 2009 (left) and undamaged Aratazowa rockfill dam in Japan, which was subjected to peak ground acceleration of 1.0 g during the magnitude 7.2 Iwate Miyagi Earthquake in 2008 (right)

In the checklist approach, weighting factors are assigned to each of the above factors. In this way, a seismic safety ranking of the dams of a dam cascade can be established. This approach has also its weakness, as the weighting factors determined by dam experts, may be subjective.

Items (vii) and (viii) are important, as it must be possible to control the water level in the reservoir after a strong earthquake to prevent the overtopping of a dam. In addition, if there are doubts about the safety of a dam, due to the observed seismic damage or the risk of aftershocks, etc., the safety of a dam can be increased by lowering the reservoir by low-level outlets. Such bottom outlets are compulsory for all dams in Switzerland, but may not be provided elsewhere. These outlets are essential for managing post-earthquake risks.

The above comprehensive list of factors affecting the seismic safety of a dam provides a more complete picture of the dam’s safety than the numerical value of the probability of failure of a dam due to ground shaking alone, which is the main parameter considered in the probabilistic safety analysis of a dam cascade.

In the deterministic seismic analysis and design of dams it is required that they are able to withstand the worst ground motion at the dam site; therefore, these dams are safe for any type of earthquake and they “cannot fail”. This means that no strengthening measures are required for dam cascades. However, in view of the seismic safety ranking of existing dam cascades as discussed above, the dams with the lowest safety ranking should be strengthened first, but there is no need to call for higher seismic safety standards for dam cascades at this time. For example, we have several dam cascades in Switzerland, and all dams must satisfy the same safety criteria irrespective if they belong to a dam cascade or not. This situation is similar to that in seismic building codes, where no distinction is made between the seismic safety of buildings located in urban (corresponding to dam cascade with many dams) or rural (corresponding to a single dam) areas.

In a dam cascade, the following failure scenarios can be considered:

1 Failure of the lowest dam: In this case, the reservoir volume of the lowest dam will be released.

2 Failure of the uppermost dam and all downstream dams are concrete dams, which can withstand overtopping: In this case, the reservoir volume of the uppermost dam will be released.

3 Failure of the uppermost dam and all downstream dams will fail due to overtopping (Note: embankment dams are most likely to fail when they are overtopped by a flood wave caused by the failure of an upstream dam): In this case, the volume of all reservoirs will be released. This is the worst-case failure scenario of a cascade.

4 Failure of the dam with the largest reservoir and all downstream dams are concrete dams, which can withstand overtopping: In this case, the largest reservoir volume dam will be released.

5 Other failure scenarios with dams that can be overtopped or dams that fail due to overtopping, reservoirs with different volumes, etc.

Based on the above failure scenarios the volume of water released at the lowest dam may vary between that of the smallest reservoir and the total volume of all reservoirs stored by the dams forming a dam cascade. It is most unlikely that due to a strong earthquake all dams will fail at the same time. The most likely scenario is that a single dam will fail and in a kind of chain reaction, the downstream dams will fail due to overtopping. As the dams are several tens of kilometers apart, the flood hydrograph at the lowest dam has to be determined by an appropriate flood wave analysis. The flood wave would be significantly less in a cascade of reservoirs of similar volume than in the case of the failure of a single dam storing the water of all reservoirs of a dam cascade.

If we assume that all dams downstream of a failed dam will also fail due to the released flood wave, then, in order to prevent catastrophic flooding of the area downstream of a dam cascade, the safety of all or some of the dams of the cascade has to be increased. Safety improvement means improving both the seismic safety as well as strengthening dams against overtopping. Strengthening embankment dams against overtopping by a large flood wave caused by an upstream dam breach may be very difficult. If we assume that the water of the reservoirs of a dam cascade is stored by a single dam, then the probability of failure of that dam during a strong earthquake would be slightly less than that of a dam cascade for the same earthquake scenario. However, dams of a dam cascade may be vulnerable to various worst-case scenarios, whereas in a single dam only one has to be considered. The volume of water released and the resulting flood wave coming from a single dam is larger than that of a dam cascade. Therefore, from the probabilistic point of view a dam cascade is more vulnerable to seismic action than a single dam. But this conclusion would also apply to a portfolio of dams irrespective of whether or not they form a dam cascade. As the seismic safety of dams of a dam portfolio is the same as that of a single dam according to current seismic design guidelines, the same applies to the dams of a dam cascade.

From the deterministic viewpoint, there is also no need to apply higher seismic safety standards to dams of a dam cascade, since the dams are designed against worst-case earthquake scenarios producing the worst ground motion at a dam site. Therefore, these dams and the dam cascade will be “safe” against any earthquake ground motion and no extra safety is required. But we know that a knowledge of the seismicity and seismic hazard at dam sites is incomplete, which includes the estimate of the worst ground motion at dam sites, therefore, it is necessary to review the seismic hazard, the seismic design criteria and the seismic safety of dams periodically or when a strong earthquake has happened. This review should be the standard practice for any hazards affecting dam safety.

4 CONCLUSIONS

Based on the discussion of the different seismic safety aspects of dams forming dam cascades, the following conclusions may be drawn:

1. At present, there is no need to apply higher seismic safety standards for dams of dam cascades. The dams forming dam cascades can be compared with dams of a dam portfolio, where no increased seismic standards are applied.

2. Rather than strengthening dams beyond the present seismic safety guidelines, it would be more effective to try to reduce the consequences of dam failure, which is useful for all types of hazards affecting the dam safety.

3. It is very hard to determine the probability of failure of dams due to earthquakes, as the seismic hazard is a multi-hazard, which besides ground shaking includes possible effects of faults in the footprint of dams, rockfalls and landslides, impulse waves in reservoir and others.

4. Safety not only includes safety during an earthquake, but also safety after an earthquake, which requires safe operation of the reservoir and/or lowering of the reservoir if there are doubts about the seismic safety of the dams and if strong aftershocks are expected, since after a strong earthquake the seismicity in the project region may remain high.

5. In an existing dam cascade, a ranking procedure for the dams is recommended that is based on a checklist and weighting factors. This is superior to a probability of failure analysis in which only ground shaking is considered.

6. In dam cascades, all dams must satisfy the same seismic safety criteria. This is an issue when dams belong to different risk categories. The highest risk category must be assigned to dams of dam cascades.

7. As knowledge on the seismic safety of dams is incomplete, periodic reviews of the seismic hazard, the seismic design criteria, and the seismic safety is necessary. Such reviews should also be made after a strong earthquake,

8. Strengthening of dams - especially embankment dams – against overtopping by flood waves caused by the upstream failure of a dam may not be feasible.

9. To apply higher seismic safety standards to dams of dam cascades beyond the current ones is not “forbidden”.

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