SEISMIC DESIGN AND SAFETY CRITERIA FOR TAILINGS DAMS: A COMPARISON WITH WATER STORAGE DAMS

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Abstract

There exist up-to-date seismic design and safety criteria for water storage dams and guidelines for the conceptual design of large dams in seismic regions, published by the International Commission on Large Dams (ICOLD). Tailings dams store waste from mining activities, which is often classified as hazardous. They are mainly embankment dams, and the way of construction differs from that of water dams. Water dams are usually completed before the reservoir is filled, whereas in tailings dams the construction of the dam and the filling with the waste material proceed stepwise at the same time, leaving an adequate freeboard to protect the tailings dam from overtopping. Thus, because of the incremental construction and reservoir filling, embankment dams are built in which consolidated tailings form also part of the embankment. In general modern dams that can resist strong ground shaking are earth core rockfill dams, where seepage through the dam body is controlled by an impervious core, which is protected from internal erosion by filters, Moreover, seepage through the foundation is controlled by a grout curtain or cut-off walls, depending on the type of foundation. Large water dams are usually founded on rock but this may not be the case for smaller embankment dams. If no sediment flushing is provided, the reservoirs formed by water dams will eventually fill up with sediments and their final state may not be too different from that of tailings dams. The difference being in the properties of tailings and in the way these tailings are placed. In water dams there is no control on how the sedimentation process occurs. Most sediment deposition will be during large floods. Both the sediments and tailings materials are assumed to liquefy under strong ground shaking. Therefore, the stored materials are basically liquids during strong earthquakes. If we take this into account, then certain types of tailings dams cannot be safe. Some recent failures of tailings dams in Brazil and Australia have shown that they failed due to static liquefaction. Therefore, it is obvious that they would have also failed under seismic action. Based on this comparison, the seismic safety requirements for tailings and water dams should be the same for the same risk classes of projects. In the case of tailings dams, the hazardous materials remain in the reservoir for hundreds of years and in the case of safety concerns the reservoir cannot be lowered as in the case of water dams, which would allow a fast increase in dam safety. Thus, the seismic safety of tailings dams should be even larger than that of water storage dams. These seismic aspects of water and tailings dams are discussed in the paper.

Keywords: tailings dam, embankment dam, earthquake safety, seismic design criteria, liquefaction

1. Introduction

Storage dams can be classified into water storage dams and tailings dams. In water dams the storage (called reservoir) can be used for water supply, irrigation, power generation, navigation, tourism, fishery and others and the storage may serve as flood protection or for regulating the flow of rivers. There are single-purpose dams, mainly smaller projects, which are used for water supply, irrigation, hydropower generation and flood protection. The large storage dams, however, are mainly multi-purpose projects. Tailings dams are single-purpose dams and serve for long-term storage of tailings mainly from the mining industry and others. The height of these dams is generally small, but there are tailings dams, which are among the highest dams in a number of countries.

Until March 11, 2011 no people have died from the failure or damage of a large water storage dam due to earthquake. However, during the magnitude 9.0 Tohoku earthquake in Japan in 2011 an 18.5 m high embankment dam failed, and the flood wave created by the release of the reservoir caused the loss of eight lives. A large number of dams have been damaged during recent earthquakes, as, for example, during the May 12, 2008 Wenchuan earthquake in China about 1580 dams and reservoirs were damaged. Most of them were small earth dams for water storage, but also some large dams were damaged.

The statistics does not look that favorable for tailings dams, as a considerable number of people were killed due to the failure of tailings dams during earthquakes as reported in [1]. Accordingly, there are about 52 tailings dams that have failed during earthquakes. Several tailings dams failed in 1965 during the La Ligua earthquake in Chile. The flow slide caused by the failure of the 35 m high El Soldado tailings dam of the El Cobre Copper Mine killed more than 200 people and 2.3 Mm^3 of liquefied tailings was released catastrophically that flowed 12 km.

The following tailings dam failures have occurred very recently: (i) the instantaneous failure of the Brumadinho tailings dam in Brazil of January 25, 2019 killed 270 people, (ii) the Mariana tailings dam failure of November 5, 2015 in Brazil killed 27 people and 44 Mm^3 of tailings were released polluting a 688 km long stretch of rivers, and (iii) the failure of a tailings dam of the Cadia gold mine in Australia of March 9, 2018. In all three cases the tailings were liquefied and in the damage analysis small earthquakes with magnitudes of less than 3, were mentioned as possible triggers. As any well-designed and constructed dam would be able to survive such small earthquakes undamaged, it must be assumed that these dams were not designed against earthquakes like water dams and must have experienced other safety problems.

Different designs of embankments for tailings dams are used that are not employed in water dams. Some of these designs are less favorable in resisting strong ground shaking than conventional dams for water storage [2]. Another factor is that dam construction is not the core business of mining companies, who are also constructing their own tailings dams.

That tailings dams are different from water storage dams is reflected by the fact that there are different technical committees of the International Commission on Large Dams (ICOLD), which are concerned with the safety of water storage and tailings dams, which, from the point of view of dam safety, is not logical as the same safety standards should apply. However, there are often different government agencies, which are in charge of the safety of these two types of storage dams, using different safety standards.

In terms of dam safety the following qualitative ranking may be established: (i) large dams for hydropower generation (multi-purpose projects), (ii) large irrigation dams and dams for water supply, and (iii) small dams and tailings dams (most tailings dams are small dams). The earthquake safety of tailings dams needs greater attention to bring the seismic standards up to those of large hydropower dams, where the highest standards are used. This will have an effect of the design of tailings dams as some designs are no longer feasible. Moreover, the fact that tailings have to be stored for very long periods of time, calls for even higher seismic safety standards than for water storage dams. This is accepted for nuclear waste storage facilities but must also be implemented in tailings storage facilities. Therefore, it is obvious that earthquake will become the governing load case for long-term storage of tailings even in areas of low to moderate seismicity. This has also been the case for nuclear power plants.

2. Main Elements of Large Water Storage Dams

A large storage dam consists of a concrete or fill dam with a height exceeding 15 m (definition of large dam according to ICOLD), a grout curtain or cut-off to minimize leakage of water through the dam foundation, a spillway for the safe release of floods, a bottom outlet (or low-level outlets) for lowering the reservoir in emergencies, and a water intake structure to take the water from the reservoir for commercial use or power production. Spillway and low-level outlets are called safety-critical elements.

As tailings dams are generally fill dams with different types of watertight elements, only earthfill or rockfill dams (embankment dams) are discussed in this paper.

If low-level outlets are missing and sediment flushing is not possible, reservoirs are eventually filled up with sediments. Close to the dam the sediment level may reach the lowest levels of the water intakes or the sill of the spillway. In industrialized areas the sediments deposited in the reservoirs may also contain hazardous substances, and therefore sediment flushing would not be allowed today, as, for example, contamination of the sediments with PCBs is not uncommon and has only been realized with the availability of very sensitive measuring equipment. The allowable levels of PCB contamination are also very low. Therefore, such substances are kept in the sediments in the reservoirs and the water dams – in terms of storage of contaminated sediments - may be like tailings dams.

3. Seismic Design and Performance Criteria for Large Water Storage Dams

3.1 Seismic Design Criteria

The seismic design and performance criteria of large dams are given in ICOLD Bulletin 148 on the Selection of Seismic Parameters for Large Dams [3]. Accordingly, the two levels of earthquakes to be considered in the design and safety assessment of large existing dams are as follows:

- Operating Basis Earthquake (OBE): The OBE may be expected to occur during the lifetime of the dam. No damage or loss of service must happen. It has a probability of occurrence of about 50% during the service life of 100 years. The return period is taken as 145 years [3]. The OBE ground motion parameters are estimated based on a probabilistic seismic hazard analysis. The mean values of the ground motion parameters of the OBE can be taken.
- Safety Evaluation Earthquake (SEE): The SEE is the earthquake ground motion a dam must be able to resist without uncontrolled release of the reservoir. The SEE is the governing earthquake ground motion for the safety assessment and seismic design of the dam and safety-critical elements (gates and valves of spillways and bottom outlets, motors, emergency power supply, hydraulic pistons, etc.), which have to be functioning after the SEE in order to control the water level in the reservoir. The SEE ground motion parameters may be obtained from a probabilistic or deterministic seismic hazard analysis [4].

The main issue related to the seismic design criteria, which are specified for three types of dams [3], 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 [3] and in another country, it is classified as a moderate consequence dam, the recurrence period is reduced to 3000 years or even 1000 years for low consequence dams. Future developments must address this issue for both water storage and tailings dams.

3.2 Seismic Performance Criteria

Today, the seismic performance criteria of dams are given in a rather general way for both the OBE and SEE [4].

The following performance criteria apply for the OBE:

(i) Dam body and foundation: No structural damage in dam is accepted; the safety-critical elements must remain functioning.

(ii) Safety-critical components and equipment (gated spillways, bottom outlets) shall be fully operable after the OBE and therefore should behave elastically during the OBE.

The following performance criteria apply for the SEE:

(i) Dam body and foundation: The reservoir must be retained safely, structural damage (cracks, deformations, leakage etc.) are accepted as long as the stability of the dam is ensured and no large quantities of water are released from the reservoir causing flooding in the downstream region of the dam.

(ii) After the SEE the reservoir level must be controlled and it must be possible to release a moderate flood by the spillway or low-level outlet(s), which must remain functioning.

(iii) After the SEE it should be possible to lower the reservoir for repair of earthquake damage, and/or to increase the safety of a dam, if there are doubts about its static or seismic safety after an earthquake or other incidents.

(iv) Safety-critical components and equipment (gated spillways, bottom outlets) must be fully operable after the SEE. Minor distortions and damage (e.g. leakage of seals of gates) are accepted as long as they have no impact on the proper functioning of the components and equipment. This means that all gates, valves, motors, control units, power supply and emergency power generators for the spillway and low-level outlets must withstand the SEE ground motions and they must be functioning after the SEE, i.e. the equipment shall be properly anchored etc. This is a new requirement [], which concerns hydro-mechanical and electro-mechanical engineers, who may not have been fully aware of their importance in the seismic safety of dams.

The OBE performance criteria can be verified by dynamic linear-elastic stress and deformation analyses - usually time history analyses -, and by rigid body sliding (and overturning) stability analyses using the peak acceleration acting in the center of gravity of the sliding mass. The safety criteria are given in terms of allowable stresses, deformation (e.g. crack width) and allowable sliding stability safety factor for the OBE load combination. For the check of the sliding stability, where a safety factor of larger than one is required, a conventional slope stability analysis can be used in which residual strength properties and the peak acceleration acting in the center of gravity of the sliding mass are required as input. The latter is obtained from a dynamic analysis of the dam.

The SEE performance criteria for the dam body will require a nonlinear dynamic analysis, which must all be done in the time domain, requiring the seismic input in the form of acceleration time histories. The main results required for the safety checks are the inelastic deformations of the dam after the earthquake. The basis of the safety checks are the failure modes of embankment and concrete dams as discussed below. The main structural failure modes can be checked based on dynamic stability analyses of slopes of embankment dams, sliding blocks of concrete dams or wedges in the dam abutments.

3.3 Seismic Failure Modes of Embankment Dams

The main seismic failure modes of embankment dams are as follows []:

- Overtopping of rockfill dam due to (i) malfunction or blockage of spillway gates (overtopping will occur after the earthquake), (ii) excessive seismic settlements of embankment dams, causing overtopping, or (iii) mass movements into the reservoir, causing impulse waves and overtopping of the dam crest.
- Internal erosion due to (i) insufficient protection of core of earth core rockfill dams, (ii) sliding movements of slopes or fault movements in the dam footprint that exceed the thickness of the fine sand filter, or (iii) damage of the contact between the core, abutment rock, concrete structures or conduits through the dam body (due to settlements, poor compaction etc.).

For the seismic safety checks, time history analyses have to be carried out, which require the seismic input in form of acceleration time histories. These time histories are not physically correct earthquake records but models of the earthquake ground motion [5]. Using ground motion models will result in a safe dam design. It is important that this is also understood by earth scientists involved in seismic hazard studies for large dams.

4. Main Elements of Tailings Dams and Long-term Dam Safety Aspects

The main difference between tailings and water storage dams is the hazardous material stored by tailings dams. Tailings dams are mainly embankment dams and they are typical for the mining industry. There are different types of sequentially raised tailings dams. The method of construction (upstream, downstream and centerline construction methods) is different from that of water storage dams as the stage-wise construction proceeds normally simultaneously with the impounding of the reservoir with tailings. Therefore, depending on the progress of the mining activities, the design of the tailings dams may be modified during its construction. This is a rare case for water dams, but heightening of water dams is also done.

Moreover, tailings dams are often raised repeatedly throughout their lives, they store a mixture of water and minerals in their reservoirs, and when they are full or mining operations cease they are left in place.

Therefore based on this general discussion, it may be concluded that in terms of the seismic safety, there should be no difference between these two dam types. However, due to the stage-wise construction, the seismic safety must also be checked for critical dam construction stages, as tailings could be released during dam construction.

The main difference from water dams is that tailings dams are single-purpose dams and that the hazardous tailings must be stored safely for very long periods of time, which exceed, for example, the lifespan of water dams. It is expected that well-maintained modern earthfill or rockfill dams could have a lifespan of several centuries. As the storage period of hazardous tailings could be “infinite” if the hazardous materials remain unchanged, earthfill or rockfill dams are most suitable for long-lasting tailings dams. Therefore, as the lifespan depends on maintenance and compliance of the dam with current safety criteria, it is required that “someone” takes care of tailings dams when, e.g., mining activities have ceased. This is a challenge for the definition of the recurrence period of the SEE ground motion, if a probabilistic seismic hazard analysis is carried out. In water dams a return period of 10,000 years has been recommended [3, 4]. But for tailings dams, if we assume a probability of exceedance of the ground motion of 10% in 10,000 years, then we will arrive at a return period of the order of 100,000 years or more. This has an effect on the dam safety, if probabilistic safety analyses are carried out. However, in water dams, the concept of the ground motion from the worst-case earthquake scenario still holds, which is questioned by people doing probabilistic safety analyses as the worst-case scenario is not related to any return period. In a deterministic seismic analysis, the worst-case earthquake ground motion is the same for the critical construction stages and the ultimate storage phase. Therefore, using the deterministic worst-case earthquake scenario concept, it would be straightforward to confirm the seismic safety of tailings dams during the very long storage phase. In a probabilistic safety analysis, fragility or vulnerability curves of the tailings dams would be required, which may only be feasible for long levee-type embankments of small height.

As we cannot assume that the safety of a tailings dam (or any other type of structure) will remain unchanged during its very long service life. Therefore, for tailings dams it is proposed to review the seismic safety periodically like in water dams, i.e. every five years. When we talk about earthquake safety then we talk about the technical safety of the project and the safety of the people, who would be endangered when the tailings were released catastrophically. Another aspect is environmental safety, which is subsidiary to technical safety of the dam. Sometimes, because the environmental safety criteria are getting stricter and stricter, the technical safety is given less attention, which would be a wrong development. But this may happen as there are usually different government agencies in charge of the safety of tailings and water dams.

In general, tailings dams do not have low-level outlets and no grout curtain or cutoff walls in the foundation. Watertightness may be provided by special types of (flexible) watertight linings of the storage area. Similar linings are also provided in some water storage projects.

5. Seismic Analysis of Tailings Dams

Depending on the risk classification of tailings dams, different methods of seismic analyses must be employed. For small embankment dams the simplified deformation analysis proposed by Bray et al. [6] may be used.

For large dams or dams with liquefiable soils or foundation materials, a dynamic analysis is required. The seismic input for the dynamic analysis of the dam-tailings storage-foundation system must be provided in the form of acceleration time histories, which represent models of the earthquake ground shaking rather than real ground accelerations [5]. This is an important aspect in practical problems as for seismic safety checks recorded acceleration time histories are only used in exceptional cases. The inelastic seismic analyses are carried out using direct time integration methods.

The use of the simple pseudo-static analysis method is outdated and shall no longer be used [7]. This is not new, as following the observations made during the 1971 San Fernando earthquake in California, it has become clear that with the pseudo-static analysis the behavior of the failed San Fernando dam, which experienced liquefaction, could not have been predicted. Although, the limitations of the pseudo-static method have been known for almost 50 years, this method is still used by some engineers and organizations, even in countries of high seismicity. This method is still defended by people and countries, who like the method! Eventually, proper analysis methods must be used everywhere.

6. Conclusions

Based on the comparison of the seismic design and safety aspects of water storage and tailings dams, the following conclusions may be drawn:

1. Most tailings dams are fill dams. Several standard dam designs and construction methods used for tailings dams are not used for water storage dams. These dams are less costly than water dams, but the fact that these designs are not used for water dams shows that they may be less safe.
2. The seismic design and safety criteria of tailings dams and water dams must be the same during the operation phase of the projects, if they belong to the same risk class.
3. Tailings must be stored safely for many centuries after ending the mining operation etc. This calls for higher seismic safety standards if probabilistic safety concepts are used. In a probabilistic seismic hazard analysis the acceptance levels may be defined similar to those used in seismic building codes, i.e. a probability of exceedance of the ground motion parameters of 10% during the

lifespan of the project, which for the long-term storage may exceed 10,000 years, i.e. this will result in return periods of 100,000 years.

4. To improve the long-term seismic safety, the water table in the tailings must be lowered. However, in low permeability tailings such processes may take a very long time or it may not be possible to lower the water table, therefore, the tailings may be liquefied due to strong ground shaking, even centuries after terminating mining operation.
5. To keep the tailings dams safe, they must be maintained after closure of mining operations. Periodic seismic safety assessments are required. Unlike water dams, where the reservoir level can be lowered to improve the safety of the dam and the safety of the people living in the downstream flood plain, this is more difficult and very costly for tailings if they have to be re-excavated or the dam has to be strengthened.
6. The seismic safety check of tailings dams with the pseudo-static analysis method is an outdated concept. For small dams empirical relations published in the literature may be used to estimate the inelastic seismic deformations; however, for larger dams, dynamic analyses have to be carried out, using acceleration time histories as input.
7. It is important to note that the seismic hazard is a multi-hazard, which, besides ground shaking, includes mass movements into the storage facilities, liquefaction of soils and tailings, and ground deformations, which must be taken into account in the seismic design and safety assessment of the tailings dams [8].
8. The risk classification of both water storage and tailings dams, which governs the seismic design criteria, is ambiguous as in different countries and organisations different classifications are used. Therefore, for the same dam different seismic design and safety criteria may be specified.

6. References

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