Seismic Safety Aspects of Gated Spillways of Large Storage Dams

Martin Wieland[1], Sanaz Ahlehagh[2]

1.Chairman, ICOLD Committee on Seismic Aspects of Dam Design, c/o Poyry Switzerland Ltd., Herostrasse 12, CH-8048 Zurich, Switzerland

2.Structural Engineer, Poyry Switzerland Ltd. Tehran, Iran

Emails: martin.wieland48@gmail.com, sanaz.ahlehagh@poyry.biz

Abstract

Gated spillways of large storage dams must be operable after the safety evaluation earthquake (SEE) such that the reservoir level can be controlled and a moderate flood can be released safely. Consequently, the gates, motors, control units and power supplies including emergency power generators must be operable and the gates should not experience any inelastic deformations causing jamming of the gates. Moreover, the spillway piers shall not exhibit any inelastic deformation in the cross-river direction, which is the weak axis of typical spillway piers. The trunnions must be able to withstand the high hydrodynamic pressures acting on the gates. Thus these elements must be designed and checked for the SEE. Vulnerable to high seismic loads are gated crest spillways due to the amplification of the support motion with respect to the ground acceleration on the rock surface. The possible seismic hazards, the seismic performance criteria of gates and electro-mechanical equipment and the dynamic analysis of spillway structures are discussed.

Keywords: Earthquake safety, dam safety, spillway gates, spillway pier, dynamic stability analysis.

1. INTRODUCTION

In 2016, ICOLD has published new guidelines on the selection of seismic parameters for large dams [2], which include seismic design criteria for (i) the dam body and (ii) the safety-critical elements, such as spillways and low level outlets. The inclusion of the safety-critical elements is new and is the consequence of the following, very general, safety and performance criteria for large storage dams subjected to strong ground shaking resulting from the so-called Safety Evaluation Earthquake (SEE):

(i) The dam must be able to retain the reservoir during and after the SEE (Note: Deformations and cracks in the dam body are accepted as long as the reservoir can be retained safely; the stability of the dam must be ensured).

(ii) The dam operator must be able to control the water level in the reservoir after the SEE (Note: It may take several months until the earthquake damage of a large dam and/or its safety-critical elements has been repaired, therefore safe operation of the reservoir during this period is a must).

(iii) It should be possible to lower the reservoir for the repair of a damaged dam and/or to increase the safety of a damaged dam or a dam, whose earthquake safety has been questioned, after an earthquake.

Item (i) has been the main concern of dam engineers since the 1930s when the first concrete and embankment dams were designed against earthquakes. However, the pseudo-static analysis method and the representation of the seismic hazard by a seismic coefficient - a value of 0.1 was used for most dams – are obsolete today and shall no longer be used, although engineers are still tempted to use this outdated concept.

Item (ii) requires the proper functioning of the spillway or a low level outlet as it has to be assumed that in a hydropower project the power plant is out of operation after the SEE. In general, ungated spillways are unproblematic if they are structurally safe. In the case of gated spillways it must be possible to open the gates such that a moderate flood with a return period of at least equal to the diversion flood can be released, as it may take several months until a storage dam project has been repaired or strengthened. The worst scenario is that shown in Fig. 1 where it was not possible to open any of the spillway gates of a run-of-river power plant, after the magnitude 8.0 Wenchuan earthquake in China in May 2008. As the structure of this power plant is made of reinforced concrete, overtopping is not a catastrophic event as it is unlikely that such a concrete structure will fail. However, overtopping of the concrete crest during extended periods of time could cause erosion damage, which may endanger the stability of the piers. Therefore, repairs must be carried out as quickly as possible. For example, progressive erosion of the rock surface was caused by the operation of the emergency spillway at Oroville dam in February 2017, threatening the stability of the emergency spillway.

Figure 1. Overtopping of run-of-river power plant due to failure of gate operation (left) and mud deposited on crest of overtopped run-of-river power plant (right) (Wenchuan earthquake in China)

Overtopping of an embankment dam, due to malfunction of spillway gates, is a far more serious safety problem than for a concrete dam, as this will ultimately lead to the failure of the dam and the catastrophic release of the reservoir. It should be added that depending on the reservoir level at the time of the earthquake and the inflow into the reservoir, it may take hours or days before the dam will be overtopped, if all gates are closed. Thus overtopping of the crest due to malfunction or inadequate spillway capacity will be a hazard that occurs after an earthquake and not during an earthquake.

Item (iii) is a matter of low level outlets, as by opening of the spillway gates, the reservoir can only be lowered to the elevation of the sill, assuming that the power plant is shut down. Although there are different opinions on the need of low level outlets of large storage dams, it is obvious that lowering of the reservoir after a damaging earthquake, increases the safety of the dam and lowers the risk for the people living downstream of a dam. For example, bottom outlets are compulsory for all dams in Switzerland.

During the SEE, some structural damage may occur in the dam body (mainly cracks and joint opening in concrete dams, and cracks and deformations in embankment dams), however, this damage shall not jeopardize the global static stability of the dam or parts of it. To avoid overtopping of dams, it is necessary that the spillways be operable after the SEE and since the repair of a damaged dam or spillway may take several months or years it must also be possible to release a moderate flood.

The present paper is concerned with the seismic safety of the supporting civil structures (piers) of gated spillways. Typically, a spillway with radial gates consists of the following key elements that must function after the SEE:

- The steel gates with motors, hydraulic system or winches with counterweights etc., control unit, power supply, emergency power generator, redundant power supply, etc., and
- The concrete piers with supports of the steel gates and anchorage of the support forces.

The main static load for the design of spillway gates is the hydrostatic load. For the seismic load case the hydrodynamic pressure according to Westergaard [3] (is used, assuming that the gate is a rigid structure. In the pseudo-static analysis, the earthquake support motion of the gates is represented by a seismic coefficient. A value of 0.1 was usually considered. This pseudo-static concept used for the seismic design of the dam body and radial gates is obsolete today as it does not account for the dynamic characteristics of the dam and gates and the time-dependent nature of the earthquake ground motion.

In view of modern dam design concepts [2] [4] where two levels of earthquakes are specified, i.e. the Operating Basis Earthquake (OBE) and the SEE, the design of the hydro-mechanical and electro-mechanical equipment is often based on the OBE, following internationally accepted design codes or guidelines for hydro-mechanical equipment, assuming that the gate structure has sufficient reserves to cope with the SEE support motions.

This concept (design for OBE and neglecting the dynamic characteristics of the gates and the earthquake motion) is too optimistic, and there is no formal check done that the gates can be opened after the SEE. This is a systematic problem, which also includes all electro-mechanical equipment.

As a result of this concept the seismic support reactions and the anchorage forces in the spillway piers are underestimated and thus, the seismic safety of the spillway piers may not be sufficient.

The seismic design of the spillway gates must be consistent with the overall seismic safety concept of the storage dam, which is the key competence of the dam engineer [4] [5]. Therefore, any technical specifications for the seismic safety of hydro-mechanical and electro-mechanical equipment must comply with the overall seismic safety concept of the dam project. Unfortunately, technical specifications are often either copies of previous specifications, which have become obsolete, or the engineers in charge of the hydro-mechanical and electro-mechanical specifications do not communicate with dam engineers or are not familiar with the seismic design of equipment. Because of these reasons, it is not known, if the gated spillways of existing dams satisfy today's seismic safety requirements.

The present paper is only concerned with the seismic safety of the spillway piers; however, we must be aware that this cannot be treated independently from the gate design.

2. SEISMIC FAILURE MODES OF SPILLWAY GATES

The main seismic failure modes of gated spillways due to ground shaking are as follows:

(i) Failure of the electro-mechanical equipment and/or failure of redundant power supply.
(ii) Jamming of gates due to inelastic deformations of gate structure, caused by, e.g., large hydrodynamic forces or by seismic deformations of piers in cross-river direction resulting in pounding damage of the gate leaf close to the top part of the pier (Note: Gates with small gap between gate leaf and embedded steel frame are more vulnerable than older gates with larger gaps).
(iii) Failure of counter weights or other components of gate operating system.
(iv) Damage of gate caused by massive elements falling on the gate such as bridge girders, gantry cranes, motors, counter weights etc.
(v) Jamming of gates due to inelastic deformations of spillway piers in cross-river direction.
(vi) Failure of tension anchorage of gate support in spillway piers or large tensile cracks and deformations in under-reinforced piers causing jamming of gates.
(vii) Jamming of gates due to differential joint movements, when structural joints in concrete are located between the two supports of, e.g. a radial gate.
(viii) Damage of spillway chute, retaining walls, flip bucket, plunge pool etc. (Note: This damage may accelerate erosion damage during spillway operation after an earthquake, but should not have any impact on the functioning of the gates).
(ix) Other failure modes depending on gate type.

Figure 2: Failure of two bays of the Shih-Kang weir caused by (mainly vertical) fault movements during the 1999 Chi-Chi earthquake in Taiwan

The most critical failure modes are those, which prevent opening of the spillway gates of an embankment dam project or a dam consisting of a concrete part and embankment dam sections after the SEE. As there are different types of gates, other failure modes may also have to be considered.

It is well known that for large dams the seismic hazard is a multi-hazard. Besides ground shaking the other seismic hazards must also be addressed, i.e. fault movement, and rockfalls and landslides (mass movements). If a concrete spillway is located on a fault, which can move during a strong earthquake, then the spillway will be destroyed as shown in Fig. 2. Rockfalls and landslides are important hazards, which have been underestimated during strong earthquakes. For example, during the magnitude 8.0 Wenchuan earthquake in China of May 12, 2008 and the magnitude 7.8 Kaikoura earthquake in New Zealand of November 14, 2016 about 100,000 mass movements were triggered.

Figure 3: Damage of spillway piers caused by rockslides during the 2008 Wenchuan earthquake in China

Figure 3 shows damage of spillway piers caused by mass movements during the Wenchuan earthquake. Mass movements are also visible in Fig. 1. Rockfalls are, however, a major problem for the unprotected electro-mechanical equipment of spillway gates and can also cause failure of radial gates as shown in Fig. 4. Mass movements can also block the spillway chute or in tunnel spillways the portal zones are those, which can be blocked or damaged by rockfalls.

Figure 4: Left-over of radial gate destroyed by rockfall during Wenchuan earthquake in China [5]

In conclusion the main failure modes of spillways are those preventing opening of the spillway gates after a strong earthquake. This is of main concern for embankment dams as overtopping will ultimately lead to dam failure, but of lesser concern for concrete dams, where limited crest overtopping can be accepted. Failure modes, which include the failure of gates, as shown in Fig. 2, where water can escape through the open space, are less dangerous than those leading to an embankment dam failure. However, this failure mode is critical, when the water can escape through all spillway openings as it may create a flood similar to that expected during the passage of the safety flood (or probable maximum flood). This may be the worst case for concrete dams. Therefore, blockage of gates and full destruction of gates must be considered.

In the case of blockage of all gates the responsible parties like to refer to blasting of the gates as the last resort. But this has not been done yet in an emergency situation and, therefore, this option cannot be considered as a feasible option.

In most gated spillways, the gates are of the same type; therefore, if a gate or its electro-mechanical components should be damaged by ground shaking, then the other gates may have the same problem. Therefore, the redundancy principle, which is important in any probabilistic safety analysis, no longer holds and the probability that one or all gates fail during a strong earthquake is the same. This can also be seen in Fig. 1.

The structural failure mode analysed in this paper is failure mode (ii) and includes the seismic safety of the spillway piers subjected to ground shaking. However, this discussion shows that the seismic safety assessment of existing gated spillways and the design of new gated spillways may be a rather complex and comprehensive task. The analysis of functionality of a radial gate after a strong earthquake is mainly based on deformation analyses of the gates and piers, whereas the gate failure is mainly a problem of the gate support and the anchorage of the static and seismic support reactions, which can be done by the analysis of both the strength and deformations.

3. SEISMIC ANALYSIS OF SPILLWAY PIER

3.1. INTRODUCTION AND CASE STUDY

Spillway gates are vulnerable to inelastic deformations caused by strong earthquakes as they can be jammed due to additional hydrodynamic forces, which were not considered in the design, or due to cross-river deformations or inadequate sliding and overturning stability of the slender spillway piers.

Seismic design concepts and design criteria for large dam projects have undergone substantial changes since their first introduction in the 1930s, therefore the earthquake safety of gated spillways, built in the past, is uncertain.

The spillway piers were usually reinforced with minimum temperature and shrinkage reinforcement. In some construction practices a contraction joint is provided in the middle of the spillway pier, reducing the effective thickness of the pier to half. Deformations of the spillway pier in cross-river direction are important for operation of the radial gates. These deformations shall be limited so that the radial gates can be operated after the SEE, provided that they do not experience any inelastic deformations and that all other equipment is functioning properly.

As a case study the spillway section, shown in Fig. 5 is investigated. The spillway system includes 7 radial gates located at the crest of an ogee spillway weir. The height of the spillway pier above ogee crest is 23.2 m. The width of each surface radial gate is 16.5 m and the piers in between are 6.0 m thick. Contraction joints are provided at the center of each pier. The spillway bridge is composed of simply supported precast bridge girders, therefore the transverse (in cross-river direction) deformations of the pier are not restrained by the spillway bridge. The vertical reinforcement of the spillway piers consists of diameter 25 mm bars at 200 mm spacing. No shear reinforcement is provided. The dynamic compressive and tensile strengths of concrete are taken as 31.5 and 3.4 MPa, respectively.

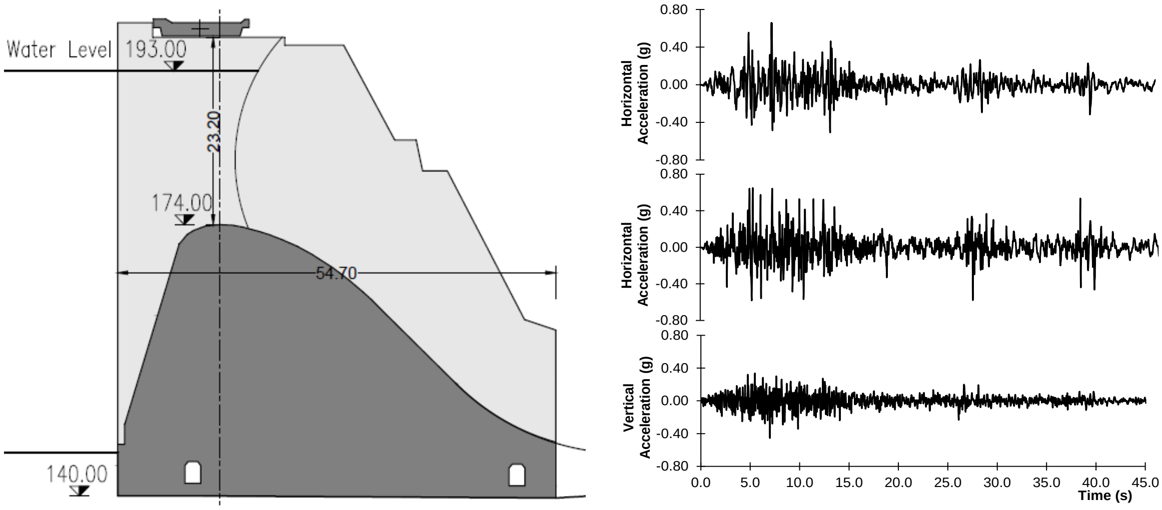

Figure 5: Cross-section of spillway pier with ogee, radial gate and bridge (left), and spectrum-matched acceleration time histories of horizontal and vertical components of the Safety Evaluation Earthquake with peak ground acceleration of 0.65 g (horizontal) and 0.45 g (vertical)

3.2. METHODOLOGY AND BASIC ASSUMPTIONS FOR SEISMIC ANALYSIS OF SPILLWAY PIER

The seismic behaviour of the pier was first investigated by a response spectrum analysis. This analysis was performed using linear material properties and the uncracked stiffness. The results showed that the spillway pier will experience significant seismic deformations at the top and the moment capacity of the pier is far more less than the seismic demand. Therefore, the pier will crack in flexure and considering the under reinforced pier, the tensile reinforcement will fracture. The crack may extend through the pier thickness which will detach the pier from the ogee mass concrete. As a result, a rigid body dynamic rocking analysis of the pier is performed in cross-river direction and the maximum displacement at top of the pier is computed.

Three sets of scaled acceleration time histories are used for the time history analysis of the pier. Each set includes the acceleration time histories of the two horizontal and vertical components of the SEE (Fig. 5).

The pier is assumed to be fixed at the connection with the ogee section. The hydrostatic water pressure on the radial gates is applied as a concentrated force at the location of trunnion supports. The added mass of water on gates in along-river direction is considered at the location of the trunnion. The added mass of water in cross-river direction is neglected. The mass of concrete bridge is applied at the nodes at the top of the pier. For the earthquake analysis the direct time integration method was used.

The acceleration time histories, peak accelerations and the acceleration response spectra at the trunnion elevation and at top of the pier, i.e. bridge support, are obtained from the time history analysis.

3.3. EIGENFREQUENCY ANALYSIS

In the first step of the dynamic analysis the vibration characteristics of the structure are computed, which include the eigenfrequencies and mode shapes. The natural periods of vibration of the four modes of vibration shown in Fig. 6 are 0.35 s, 0.20 s, 0.12 s and 0.09 s.

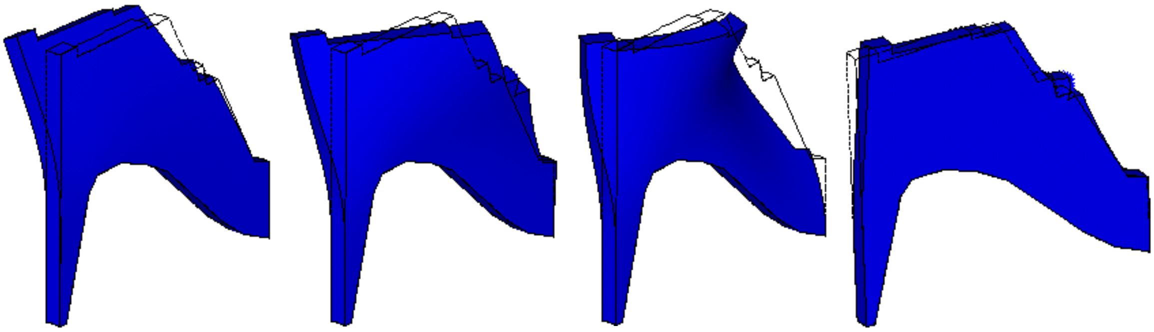

Figure 6: First four vibration mode shapes of the spillway pier

3.4. LINEAR TIME HISTORY ANALYSIS

The linear elastic dynamic analysis of the pier was carried out using three different acceleration time histories. Fig. 7 shows the time histories of the absolute acceleration and displacement in cross-river direction on top of the pier for one of the three ground motions. The maximum value of absolute acceleration is about 1.6 g, which is about 2.5 times the peak ground acceleration. The maximum top displacement of the slender pier is about 70 mm.

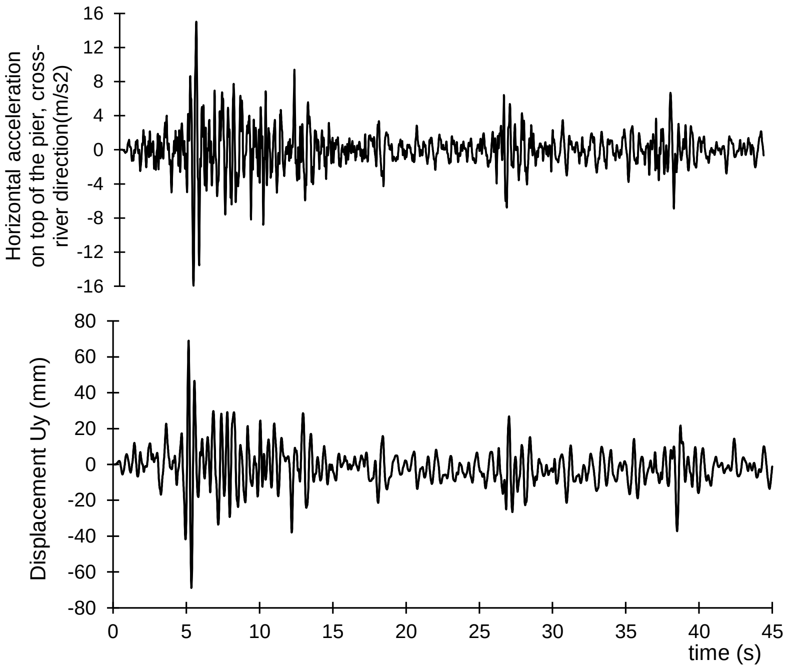

Figure 7: Time histories of absolute acceleration (top figure) and relative displacement (bottom figure) in cross-river direction on top of the spillway pier

Figure 8 shows the time history of the bending moment in the spillway pier at the ogee elevation as well as the dynamic cracking moment. For the axial compressive force of 1000 kN, the dynamic cracking moment of the 3.0 m thick concrete pier is 5600 kNm/m.

The spillway piers were normally reinforced with minimum temperature and shrinkage reinforcement. In the analyzed prototype the reinforcement at the location of the maximum bending moment (near the ogee crest) is diameter 25 mm at 200 mm spacing. For this section the nominal moment capacity of reinforced concrete section is less than the cracking moment of concrete. As yielding and nominal moment capacities of the pier are less than the cracking moment, brittle failure is expected.

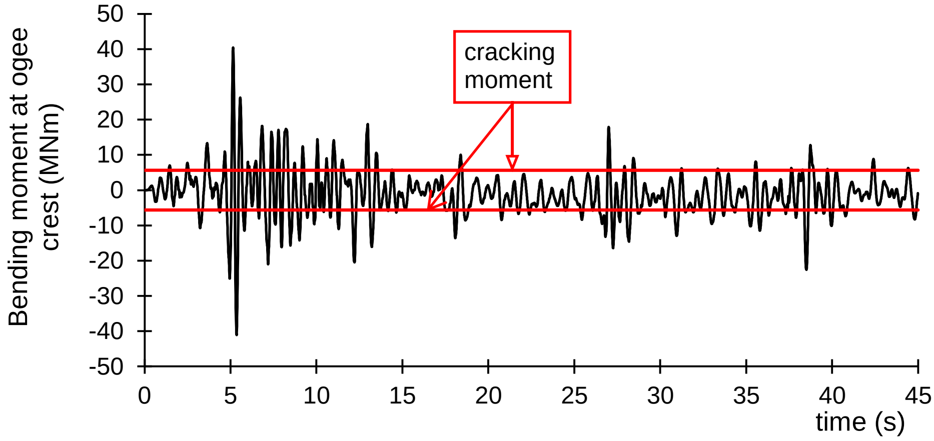

Figure 8: Bending moment time history at bottomof pier,dynamic crackingmomentis shownin red

3.5. DYNAMIC STABILITY ANALYSIS OF SPILLWAY PIER IN CROSS-RIVER DIRECTION

The results of the linear-elastic time history analyses have shown that the concrete pier will crack in flexure and as the section is lightly reinforced, fracture of flexural reinforcement is probable. Therefore, it can be assumed that the pier will fracture at the elevation of horizontal lift joints close to the ogee crest and that the part of the pier above that crack is separated from the base of the spillway. Accordingly, a dynamic stability analysis was carried out for the separated concrete block of the spillway pier, including a rocking and sliding block analysis in cross-river and along-river directions, respectively. The concrete block separated by a horizontal crack is assumed to be rigid.

It is worth noting that in a seismic rigid body analysis several assumptions have to be made, especially those related to the crack separating the upper part of the pier from the lower one at ogee elevation.

The detached part of the spillway pier will eventually overturn if an overturning moment higher than the resisting moment is applied and sustained. However, under earthquake excitation, large overturning moments occur for only a fraction of a second in each cycle. Although rocking occurs, the structure may not become unstable as rocking motion about a horizontal surface is a reversible process.

Figure 9 shows the maximum cross-river displacement at the top of the detached pier obtained from a rigid body rocking analysis due to three sets of earthquake time histories. The maximum cross-river displacement varies from about 170 to 280 mm and occur at different times. In this figure also along-river sliding displacements obtained from a rigid body sliding analysis due to three sets of earthquake time histories are shown. The maximum residual displacement of about 75 mm is estimated assuming that the ogee block under the pier will not experience any displacements in case of earthquake.

From Fig. 9 it can be clearly seen that after the earthquake there is no residual tilting of the pier, however, sliding is a cumulative process, which continues if the duration of strong ground shaking would be extended. This is not the case for the rocking motion where the duration of strong ground shaking has hardly any effect on the maximum cross-river displacement.

These rigid body displacements may be different at the two supporting piers of the radial gate and may lead to gate damage and/or jamming of the gate.

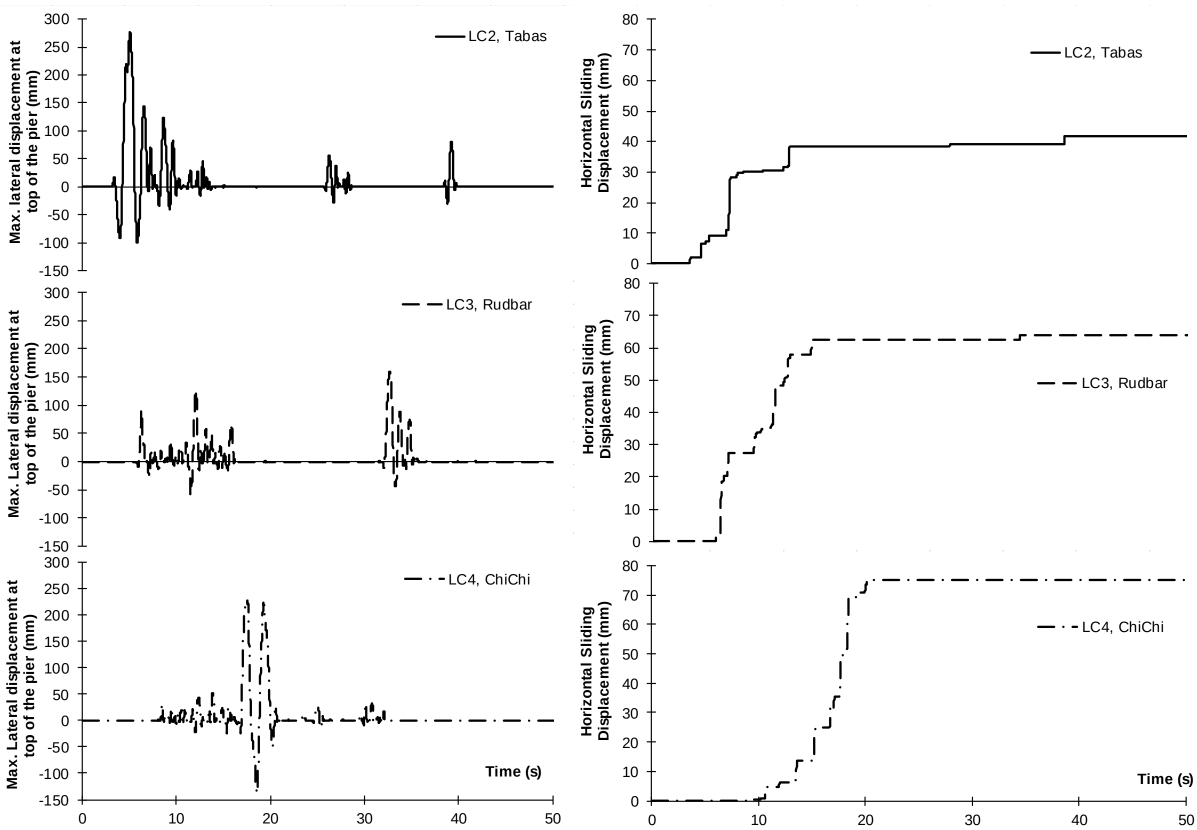

Figure 9: Rocking motion and sliding displacement of detached concrete pier: Time histories of cross-river displacement at top of spillway pier (left) and along-river sliding displacement (right) due to three spectrum-matched acceleration time histories with peak ground acceleration of 0.65 g

4. Discussion of Seismic Performance of Spillway Pier

Inelastic deformations of the spillway pier in cross-river direction will endanger proper functioning of the spillway gates. The linear-elastic dynamic analysis of un-cracked pier of an existing spillway showed that the maximum dynamic cross-river deflection at the top of the pier can be about 70 mm during the SEE. This value will increase if the cracked stiffness of the pier is taken into account.

The maximum bending moment demand of the spillway pier exceeds the cracking moment capacity of concrete at the base of the pier. As the spillway pier analysed is under-reinforced, it is likely that cracks extend through the whole pier during SEE and the spillway pier be separated from the massive ogee structure by a horizontal crack. The maximum displacement of the rigid body rocking analysis of the detached concrete pier in cross-river direction is 280 mm while the horizontal sliding displacement in along-river direction is 75 mm.

The high deformations obtained from the dynamic analysis and high flexural demands signify the necessity of strengthening of the spillway piers.

5. Conclusions

The main seismic failure modes of gated spillways are (i) failure of opening of the gates after an earthquake causing overtopping of the dam body and failure of embankment dams - limited overtopping of concrete dams may be accepted -, and (ii) structural failure of the gates, resulting in uncontrolled release of water from the reservoir and flooding of the downstream region of the dam. Therefore, the following conclusions may be drawn:

- Spillway gates must be functioning after the safety evaluation earthquake (SEE), i.e. the seismic design criteria for the gated spillway must be the same as those for the dam body.

- The earthquake hazard is a multi-hazard and all hazards must be considered in the seismic safety check. Besides ground shaking, rockfalls may damage gates and or the electro-mechanical equipment and power supply needed for opening the gates.
- Appropriate methods of dynamic analysis must be selected, taking into account the dynamic characteristics of the gates and piers as well as the oscillating nature of the earthquake ground motion. The pseudostatic analysis method shall no longer be used as it is obsolete and gives incorrect results.
- Spillway piers must be able to withstand the seismic action in along-river and cross-river directions. The cross-river direction is most critical for slender piers. The resulting pier deformations may damage the gate due to pounding near the top, causing jamming. The cross-river component has been ignored in most existing spillways.
- In cases where the spillway gates and piers have been designed for the operating basis earthquake ground motion, a check for the SEE must be carried out as the gate must be functioning after the SEE.
- The dynamic rocking stability analyses show that the maximum cross-river deformation at the top of the pier depends strongly on the seismic input used, even for the case where the acceleration time histories match the same target response spectrum.

6. References

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