Seismic Design and Safety Aspects of Bottom Outlets, Spillways and Intake Structures of Large Storage Dams

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SUMMARY:
According to the seismic performance criteria of the International Commission on Large Dams it is accepted that a dam can be damaged during the safety evaluation earthquake, provided that the reservoir can be stored safely. It must also be possible to control the reservoir and to release moderate floods after a strong earthquake. Thus the bottom outlets, spillways, intake structures and all related power supply and control facilities must remain operable. Designers of hydro-mechanical and electro-mechanical equipment and components follow their own guidelines and criteria, which may not be compatible with those of the dam engineers. The seismic design and performance criteria of these components and their behaviour during recent earthquakes are presented. Furthermore, attention is drawn to the fact that the seismic hazard is a multiple hazard comprising ground shaking, fault movements, mass movements and other site-specific hazards.

Keywords: Large dams, seismic design criteria, hydro-mechanical equipment, electro-mechanical equipment

1. INTRODUCTION

Large concrete and embankment dams have been designed against earthquakes since the 1930s. For about 50 years the pseudostatic method of analysis has been used in conjunction with a seismic coefficient of 0.1. In 1989 the International Commission on Large Dams (ICOLD) has introduced modern seismic design criteria for dams by introducing two levels of design earthquakes which were revised in 2010 (ICOLD 2010). However, there has been no clear seismic design concept for the appurtenant structures and the hydro-mechanical and electro-mechanical components of large dams for hydropower generation. Thus the seismic design of these structures and components varies almost from country to country or even from project to project. The reasons for this unsatisfactory situation are that (i) ICOLD and the dam safety agencies in the different countries are mainly concerned with the safety of the dam body and (ii) dams and hydropower plants are excluded from the scope of most earthquake codes for building structures.

In practice the seismic design of the appurtenant structures is done by structural engineers, the design of the hydro-mechanical equipment by mechanical engineers and that of the electro-mechanical equipment by electrical engineers and equipment suppliers. Many of these engineers are not familiar with the seismic safety concept of large dam projects. Although the pseudostatic analysis concept was superseded by the new seismic design criteria introduced in 1989, it had little impact on the way appurtenant structures and equipment are still designed, in particular in countries of low to moderate seismicity. The appurtenant structures and components were designed for the OBE (operating basis earthquake) ground motion almost independent of their importance. This was a misconception as the designers of these structures and components were of the opinion that the two-level design earthquake concept used for the dam body is also applicable to all other structures and components and that the seismic design with the OBE (serviceability limit state) were sufficient.

Moreover the equipment is usually specified by hydro-mechanical and electrical engineers and reference is given to corresponding design guidelines, which are not project related. This may lead to the situation that the seismic design of the equipment is inadequate or that it is not properly installed.

For large dam projects the equipment and components may be classified as follows;

- Safety class 1: All elements related to the safe control of the reservoir, i.e. bottom outlets and spillways are defined as safety-critical or safety-relevant elements.

- Safety class 2: All structures and components related to power production (penstock, power intake, powerhouse, tunnels, caverns, turbines, switchyard, transmission lines etc.), water supply, irrigation, navigation etc.

- Safety class 3: Other items which can easily be replaced/repaired when damaged and whose failure has acceptable consequences.

For each of these three safety classes project-specific design criteria shall be given.
It is obvious that safety-relevant equipment, which must function after the SEE, must be designed for the SEE.

The pseudostatic analysis, which, due to its simplicity, is liked by all engineers, can still be used for very stiff components, where the maximum inertial force can be taken as the product of the mass of the component and the peak support acceleration.

For small components a seismic qualification may also be feasible using shaking tables. But this is seldom possible for large hydro-mechanical and electro-mechanical components.

The bottom outlet and spillway are safety-relevant elements. They include civil as well as hydro-mechanical and electro-mechanical components, i.e. gates, valves, hoisting/hydraulic equipment, control units and software, power supply systems, etc. All components, which may affect the proper functioning of the gates and valves must resist the effect of ground shaking and shall be protected from the impact of debris in buildings etc.

In the subsequent sections emphasis is put on safety-relevant elements and specific hydro-mechanical elements for power production.

2. EARTHQUAKE HAZARD IN LARGE DAM PROJECTS

The earthquake hazard is a multi-hazard. With respect to large dams we can distinguish between the primary hazards, which are due to the natural environment, e.g. ground shaking, fault movement, rockfalls etc. and the secondary hazards caused by the earthquake-induced failure of structures or components (see Wieland (2010) and (2012) for a detailed discussion of seismic hazards affecting dams and hydropower plants) . For example, the flooding of the powerhouse due to the failure of a penstock caused by rockfall is a secondary hazard. The same applies to the consequences of overtopping of a dam due to the failure of a power generator for operating spillway gates due to rockfall or the flood wave caused by the failure of a radial gate due to rockfall, etc. All these primary and secondary hazards have occurred during the May 12, 2008 Wenchuan earthquake in China.

A summary of the main seismic hazards to be considered for the different appurtenant structures and components in mountainous regions is given below.

- Electro-mechanical equipment located in a surface powerhouse or the dam crest: support shaking and rockfall.
- Switchyard components: ground shaking, earthquake-induced settlements and ground failure

in fill areas.
- Transmission towers: rockfall.
- Hydro-mechanical equipment: support shaking and rockfall.
- Buried penstocks: fault movements.
- Surface penstocks: rockfall and fault movements.
- Tunnels: fault movements.
- Intake and outlet structures and tunnel portals: mass movements.
- Structures located beneath excavated slopes; mass movement.
- Surface powerhouse: ground shaking and rockfalls.
- Emergency power supply systems: ground shaking and rockfall.
- Pressure tunnels, penstocks, and for gates and valves: hydrodynamic pressures caused by ground shaking.

The above list is incomplete as the critical seismic hazards depend both on the site conditions and the project layout and design. It can be noted that ground shaking and rockfalls (mass movements) are the critical hazards for most structures and components (Fig. 1).

Figure 1. Mass movements in epicentral region (left) and mass movement blocking tunnel entrance (right) (Wenchuan earthquake, China)

3. SEISMIC DESIGN CRITERIA FOR LARGE HYDROPOWER PROJECTS

The following design earthquakes are needed for the seismic design of the different structures and elements of a large hydropower project (ICOLD 2010, Wieland 2012b):
- Safety Evaluation Earthquake (SEE): The SEE is the earthquake ground motion a dam must be able to resist without uncontrolled release of the reservoir. It is the governing earthquake ground motion for the safety assessment and seismic design of the dam and safety-relevant components, which have to be functioning after the SEE. The ground motion parameters can be obtained from a site-specific probabilistic or deterministic seismic hazard analysis.
- Design Basis Earthquake (DBE): The DBE with a return period of 475 years is the reference design earthquake for the appurtenant structures. The DBE ground motion parameters are estimated based on a site-specific probabilistic seismic hazard analysis.
- Operating Basis Earthquake (OBE): The OBE may be expected to occur during the lifetime of the dam and is used for the serviceability check of the dam and the safety-relevant elements. The ground motion parameters are usually obtained from a site-specific probabilistic seismic hazard analysis.
- Construction Earthquake (CE): The CE is to be used for the design of temporary structures and river diversion facilities such as cofferdams, diversion tunnels and intake. The return period of the CE of the diversion facilities may be taken as that of the design flood of the river

diversion.

DBE, OBE and CE ground motion parameters are usually determined by a probabilistic approach (mean values of ground motion parameters are recommended), while for the SEE ground motion deterministic earthquake scenarios may also be used (84 percentile values of ground motion parameters shall be used).

If reservoir-triggered seismicity (RTS) is possible then the DBE and OBE ground motion parameters should cover those from the critical and most likely RTS scenarios as such events are like to occur within years after the start of the impounding of the reservoir.

The following design earthquakes are recommended for the different appurtenant structures and hydro-mechanical and electro-mechanical components of a hydropower plant if no corresponding codes or guidelines exist:

Safety class 1: Bottom outlets and spillways: Design for SEE and OBE (serviceability)

Safety class 2: All structures and components related to power production (penstock, power intake, powerhouse, tunnels, caverns, turbines, switchyard, transmission lines etc.), water supply, irrigation, navigation etc.: Design for DBE with high importance factor (Recommendation: Design according to earthquake building code as minimum requirement).

Safety class 3: Other items which can easily be replaced/repaired when damaged and whose failure has acceptable consequences: Design for DBE according to earthquake building code.

4. SEISMIC SAFETY ASPECTS OF CRITICAL HYDRO-MECHANICAL EQUIPMENT

The safety-relevant elements of a dam, which must be operable after the SEE, are mainly spillways and bottom outlets. The critical components are gates and valves, their electrical and electronic components such as power supply, emergency power supply, control systems and software. These components must be functioning after a strong earthquake. For example, it must be possible to release a flood with a return period of say 200 years after a strong earthquake. This flood depends on the type of the dam. For embankment dams, which are vulnerable to overtopping the return period of this flood is longer than for a concrete dam, where limited overtopping of the crest is acceptable.

It must also be assumed that the turbines and generators of a hydropower plant are shut down after strong earthquakes. This may be due to damage of the equipment in the powerhouse, but more likely equipment of the switchyard including transformers and also transmission towers may be damaged. In mountainous regions transmission towers are very vulnerable to rockfalls as observed during the 2008 Wenchuan earthquake in China.

Also during this earthquake a control panel for operating the gates of one intake tower of the 156 m high Zipingpu concrete face rockfill dam overturned and therefore it was not possible to operate the gates for a few days. At the time of the Wenchuan earthquake the Zipingpu reservoir with a capacity of 1100 Mm^3 was less than 30% full and despite the earthquake damage of the dam there was no risk for the people living downstream of the dam. However, after the earthquake, due to heavy rainfall, a moderate flood arrived in the reservoir and it was not possible to operate some of the important gates due to the overturned control panel (Fig. 2). Therefore, because some of the gates could not be operated the risk of dam failure increased significantly during that period. Fortunately, the damaged control panels could be repaired within a few days. The failure of this control panel, which could have been prevented easily if the panel would have been anchored to the wall, shows that (i) a failure of a single element of a safety-relevant system could have major consequences, and (ii) the supplier and contractor for the installation of the control panel were not aware of the earthquake hazard and earthquake-resistant installation of equipment.

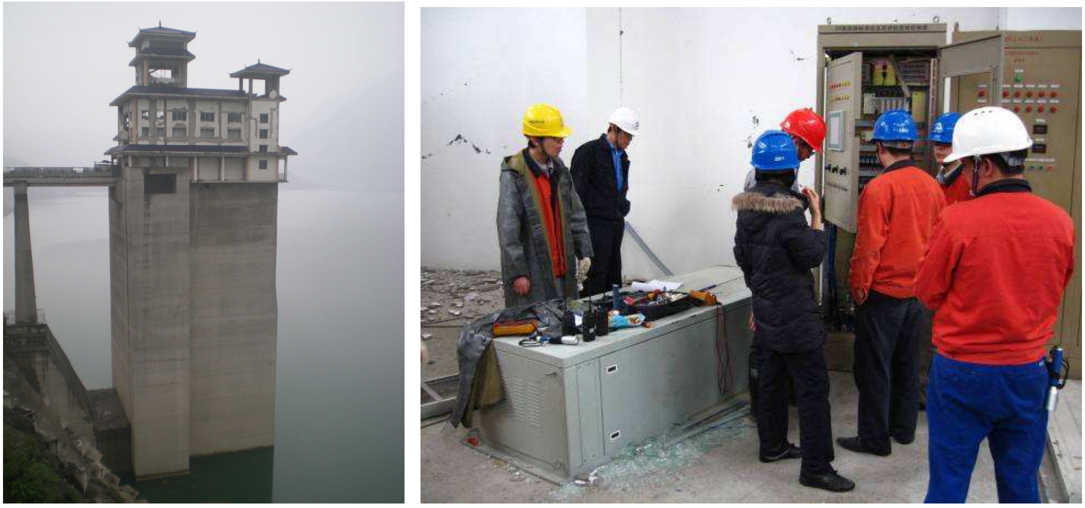

Figure 2. Intake tower and damaged gate room structure on top (left) and overturned control panel for operating the gates (right) (Zipingpu dam, Wenchuan earthquake, China)

The problem is that the communication between structural, mechanical and electrical designers, contractors, and suppliers is lacking and that people, who have the necessary (interdisciplinary) know-how are not involved in the design and the preparation of technical specifications. This means that the dam engineer should review the seismic designs and specifications of the equipment and installations for safety-relevant elements.

Furthermore, in the epicentral region of the Wenchuan earthquake several low-head run-of-river power plants were overtopped as the electricity supply was interrupted and also in one case the generator for the emergency power supply was damaged by rockfall. Therefore, the spillway gates could not be opened and as the power plants were also shut down no water could be released from the reservoir after the earthquake. This scenario has caused the overtopping of a few run-of-river power plants. The structural damage due to overtopping of the concrete spillway structure and the gates was minor. The main damage was due to the deposition of silt and mud, which required extensive cleaning and/or the replacement of sensitive electro-mechanical equipment.

The access to remote dam sites after a strong earthquake is a problem that shall not be underestimated. Therefore, heavy construction equipment for the repair of damaged dams and hydro-mechanical equipment cannot be moved to every dam site within a short period of time. For example, the access road to the 132 m high Shapai RCC (roller compacted concrete) arch dam was blocked for about ten months after the Wenchuan earthquake. This means, that a damaged dam must be able to store water for an extended period of time and that during this period the reservoir must be operated safely. This is only possible when all the safety-relevant equipment is functioning properly after a strong earthquake such as the SEE.

During the March 11, 2011 Tohoku earthquake in Japan, dams were also subjected to strong ground shaking and after the earthquake 400 dams had to be inspected. In the case of the few small dams located in the area of radioactive contamination, which were not accessible due to the radiation, the spillway gates had to be opened permanently to prevent overtopping and failure of these 'abandoned' dams. Again, this was only possible where the gates were fully operational after the earthquake.

The safety-relevant elements of a hydropower plant can be compared with the emergency cooling systems of nuclear power plants, which must also be fully functional after extreme seismic events. The consequences of the failure of these elements – even minor ones - may be catastrophic.

5. EARTHQUAKE VULNERABILITY OF HYDRO-MECHANICAL AND ELECTRO-MECHANICAL EQUIPMENT

The earthquake damage of hydro-mechanical and electro-mechanical equipment is mainly due to ground shaking, support movements (settlements), impact of rocks. falling debris (mainly non-structural elements and infill walls) in structures, overturning (deficient anchorage of equipment), flooding, fire, dirt and dust etc.

Most vulnerable to ground shaking are slender electrical components with high mass and high centre of gravity, which must be properly supported.

The seismic design of the hydro-mechanical and electro-mechanical equipment of safety classes 1 to 3 can be carried out according to the recommendation given in Section 3.

Most equipment is vulnerable to rockfall and falling debris within a building. The best way is to eliminate the rockfall hazard. This can be done by constructing an underground powerhouse, by selecting a safer place for the switchyard, to install important and expensive equipment away from steep slopes, to clear slopes from unstable rocks, to provide slope protection by shotcrete, anchors, drainage etc., to provide berms in steep slopes, to install nets near vulnerable structures etc. In some cases it may be necessary to design structures for rockfall impact.

Figure 3. Damage of gate of power intake due to rockfall (Wenchuan earthquake, China)

In the case of transmission towers site selection in combination with slope clearing and protective walls or nets may be required. As the Wenchuan earthquake has shown, transmission towers located in mountainous regions are very vulnerable during strong earthquakes. The effect of rockfall on gates and transmission towers is shown in Figs. 3 to 6.

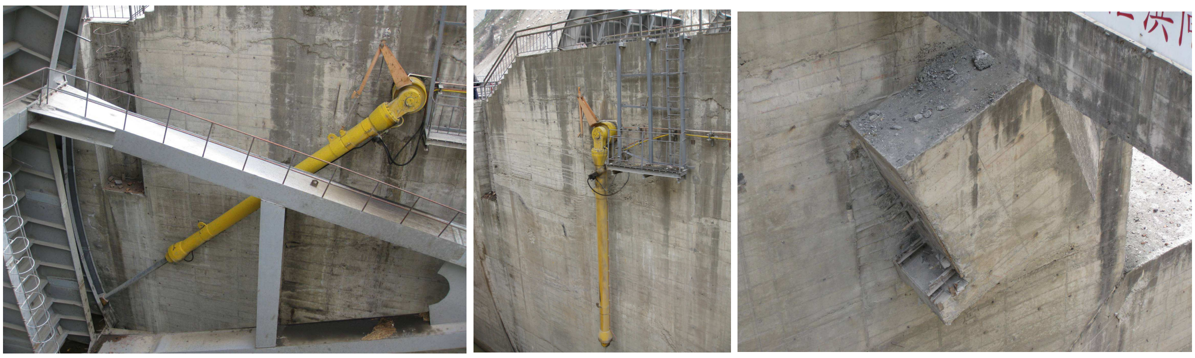

Figure 4. Failure of radial gate of Taipingyi weir due to rockfall (Wenchuan earthquake, China): Intact radial gate (left), hydaulic piston of failed gate (centre) and trunnion of failed gate (right)

Figure 5. Failure of transmission tower caused by rockfall (left) and failure of switchyard components caused by ground shaking and settlement of fill material (right) (Sefid Rud dam; 1990 Manjil earthquake, Iran).

Figure 6. Damage of Shapai powerhouse due to rockfalls and flooding (left) and sediments from flooding due to penstock failure inundating the powerhouse and switchyard (right) (Wenchuan earthquake, China)

6. SEISMIC DESIGN ASPECTS OF PENSTOCKS AND HYDRODYNAMIC PRESSURES

Penstocks, plugs of diversion tunnels, gates in bottom outlets, intake structures and spillways, valves and other hydro-mechanical components of the pressurized water system in hydropower plants have rarely been designed for the hydrodynamic pressures, which may be caused during a strong earthquake. The hydrodynamic pressure according to Westergaard is assumed for gates of surface spillways, but not for gates located in tunnels or valves in large diameter penstocks.

Figure 7. Failure of penstock near Shapai powerhouse: Water jet from failed expansion joint and flooding of powerhouse area (left) and detail of damaged expansion joint (right) (Wenchuan earthquake, China)

Up to now no case of a penstock that has failed or been damaged due to an earthquake, is documented in the literature. During the Wenchuan earthquake the expansion joint of the penstock of the Shapai arch dam project failed near the powerhouse and inundated the powerhouse, switchyard and some of the surrounding buildings and sediments were deposited in the flooded area (Fig. 7).

As earthquakes affect all components of a hydropower plant, hydrodynamic actions have also to be checked for all hydro-mechanical components. It may be argued that in the pressurized water system the water hammer is already investigated and that the emergency shut-down of a penstock may cause the maximum hydrodynamic pressures. As discussed in the subsequent sections, the hydrodynamic pressures due to valve regulation are larger than those due to earthquakes in long penstocks or pressure tunnels with a natural period of vibration of the water of several seconds. However, in relatively short penstocks with fundamental eigenfrequency of the oscillating water mass in the range of the dominant frequencies of the earthquake ground motion, the situation may be the opposite (Wieland, 2012a).

The earthquake-induced hydrodynamic pressures in penstocks have been discussed by Wieland (2005). For low head schemes the hydrodynamic pressure can greatly exceed the hydrostatic one. These pressures may not only jeopardize the safety of the penstock – negative pressures may cause local buckling - but also the gates and valves located in relatively short intake tunnels and penstocks, respectively. Moreover, the plugs in closed diversion tunnels may experience very high hydrodynamic forces during an earthquake.

7. CONCLUSIONS

The following conclusions may be drawn:

- Spillway gates and gates or valves of bottom outlets must be functioning after the safety evaluation earthquake and thus the performance criteria for these safety-relevant elements are stricter than those for the dam body. Power supplies for these gates and valves as well as control units, hoisting equipment etc. must be designed for the safety evaluation earthquake ground motion.
- The earthquake hazard is a multi-hazard and all aspects must be taken into consideration. The rockfall hazard is a major hazard for equipment located on the surface in mountainous regions.
- Both primary seismic hazards from the natural environment and secondary hazards due to the earthquake-induced failure of a structure or component must be considered.
- The seismic design criteria for safety-relevant elements such as spillways and bottom outlets are the same as those for the dam body.
- In the absence of any seismic design specifications, the seismic design of appurtenant structures for power production, water supply, irrigation, navigation etc, shall as a minimum requirement correspond to that of building structures with high importance factor. For the other structures and components a lower importance factor as given in earthquake codes for buildings may be used.
- Appropriate methods of dynamic analysis must be selected. The pseudostatic analysis can only be used for rigid components; however, the seismic coefficient shall correspond to the maximum support acceleration of the equipment.
- It must be ensured by proper communication between the civil, hydro-mechanical and electrical design teams that consistent seismic design criteria are used for the whole dam project.
- Proper fastening of the equipment to the supporting structure is essential for all pieces of equipment and components.
- The hydrodynamic pressures in short penstocks and short pressure tunnels can be quite high during strong earthquake shaking. In this case the assumption of an incompressible fluid leads to an underestimate of the hydrodynamic pressures.

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REFERENCES

ICOLD (2010), Selecting seismic parameters for large dams. Guidelines, Revision of Bulletin 72, Committee on Seismic Aspects of Dam Design, International Commission on Large Dams, Paris.

Wieland, M. (2005). Hydrodynamic pressures, Int. Journal Water Power and Dam Construction, October.

Wieland, M. (2010). Seismic aspects of large dams: Lessons learnt from the May 12, 2008 Wenchuan Earthquake, Proc. Int. Symposium on Dams & Sustainable Water Resources Development, 78th ICOLD Annual Meeting, Hanoi, Vietnam, May 20-26.

Wieland, M. (2012a). Seismic aspects of bottom outlets, spillways, intake structures and penstocks of large storage dams, Proc. International Symposium « Dams for a changing World – Need for Knowledge Transfer across the Generations & the World », Kyoto, Japan, June 5.

Wieland, M. (2012b). Seismic design and performance criteria for large storage dams, Proc. 15th World Conference on Earthquake Engineering, Paper 638, Lisbon, Sep. 24-28.