

# **Seismic Aspects of Underground Structures of Hydropower Plants**

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## **Abstract**

Hydropower plants with underground powerhouse contain different types of underground structures namely: diversion tunnels, headrace and tailrace tunnels, access tunnels, caverns grouting and inspection galleries etc. As earthquake ground shaking affects all structures above and below ground at the same time and since some of them must remain operable after the strongest earthquake ground motion, they have to be designed and checked for different types of design earthquakes. The strictest performance criteria apply to spillway and bottom outlet structures, i.e. tunnels, intake, outlet, underground gate structures, etc. In the seismic design of underground structures it must be considered that the earthquake hazard is a multi-hazard, which includes ground shaking, fault movements, mass movements blocking entrances, intakes and outlets, etc. Underground structures for hydropower plants are mainly in rock, therefore underground structures in soil are not discussed in this paper. Special problems are encountered in the pressure tunnels due to hydrodynamic pressures and leakage of lining of damaged pressure tunnels. The seismic design and performance criteria of underground structures of hydropower plants are discussed in a qualitative way on the basis of the seismic safety criteria applicable to large dams, approved by the International Commission on Large Dams (ICOLD).

**Keywords:** seismic hazard, underground structures, hydropower plants

## **Introduction**

The general perception of engineers is that underground structures in rock are not vulnerable to earthquakes as tunnels and caverns are assumed to move together with the foundation rock. Accordingly, in the design of underground structures earthquake action has been disregarded in most parts of the world and many tunneling engineers would still consider any earthquake damage as an acceptable risk. This attitude may have been justified some 30 years ago, but today we know much more about earthquakes and underground structures. As a matter of fact, a significant number of tunnels have experienced some damage during earthquakes.

The following aspects have to be considered: (i) tunnels and caverns in rock; and (ii) installations and non-structural elements located in underground structures.

Earthquake design aspects of tunnels in soil are not discussed in this paper as tunnels for hydropower plants are mainly in rock.

The earthquake safety and seismic design of underground structures in soil is of primary interest for urban transportation systems (subways) and also for highway and railway tunnels, where the whole tunnel or parts of tunnels with shallow overburden are located in soil. The seismic design of tunnels in soft soil has been standard practice in countries like Japan and Taiwan.

The earthquake damage, which can cause problems in underground structures of hydropower plants may be quite different from that in highway and railway tunnels.

In railway tunnels a distortion of the track, a small lateral offset at a rock joint or a piece of rock on the track can have severe consequences especially in the case of high speed trains. In highway tunnels safety problems are due to debris (rocks, lining elements (especially unreinforced linings and failing non-structural elements) but also the local failure of lifelines and safety systems may cause accidents and fires. Earthquakes may be the worst-case events as they will also affect all safety systems in tunnels and can make them inoperable, i.e. sprinklers may not function, lighting and communication may fail, emergency doors may be blocked, etc.

In connection with feasibility studies for underground nuclear power plants, a comprehensive compilation of earthquake effects on underground structures was prepared by Abgabian in 1985. This study lists about 150 events. Since then several strong earthquakes have occurred increasing this number of incidents. Therefore, it is premature to state that underground structures are safe from earthquakes.

### **Underground structures in hydropower plants**

The underground structures of large hydropower plants may include the following (Fig. 1):

1. Diversion tunnel(s), intakes, outlets and plugs (temporary structure);
2. Headrace tunnel with intake and surge tank (shaft and chambers);
3. Tailrace tunnel with outlet;
4. Pressure tunnels and shafts;
5. Powerhouse, transformer etc. caverns;
6. Access and connecting tunnels;
7. Inspection and grouting galleries and shafts etc.
8. Spillway tunnels with intakes and outlets (safety-relevant element);
9. Tunnel for bottom outlet with intakes, outlet and valve/gate chamber/cavern (safety-relevant element), etc.

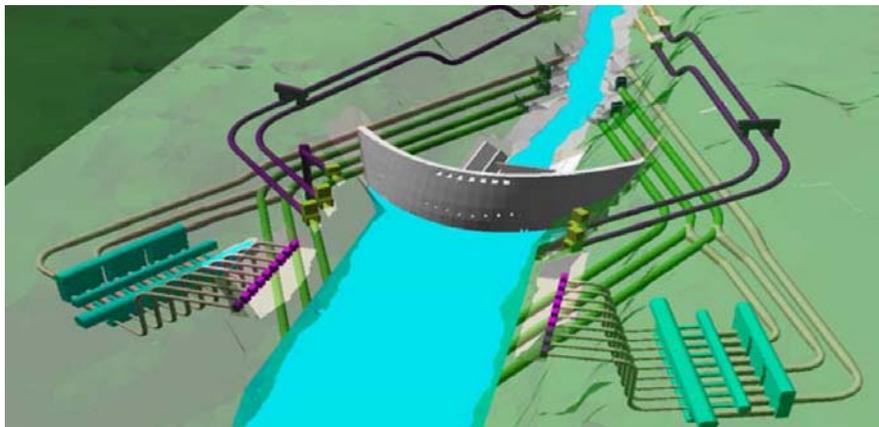


Figure 1: Layout of the 285.5 m high Xiluodu arch dam with underground structures and world's largest powerhouse caverns (one underground powerhouse on each bank of the reservoir; location: Jinsha River, China; installed capacity: 13.86 GW)

The strictest seismic safety and performance criteria apply to items 9 and 10 as discussed in the subsequent sections; they must remain functional after a severe earthquake.

### **Earthquake hazard a multi-hazard**

Recent earthquakes have demonstrated that earthquakes are multiple hazard events, which can affect large dam projects in many different ways, i.e.

- ground shaking causing vibrations in underground structures, installations and equipment;
- movements at active faults crossing underground structures or movements along discontinuities (joints, bedding planes, fissures, faults, shear zones), which can be activated during a strong earthquake, causing local damage, leakage and seepage;
- rockfalls causing damage to gates, intake and outlet structures, retaining walls, electro-mechanical equipment , cables and conduits;
- deep seated mass movements involving underground structures, and
- mass movements blocking access roads to dam sites and tunnel entrances, etc.

Usually design engineers are focusing on ground shaking and tend to neglect the other hazards. Therefore, it is recommended to prepare a hazard matrix in which along one axis the different seismic hazards are listed and along the other one the different underground structures (caverns, tunnels, galleries etc.), installations (non-structural elements) and equipment. For each type of seismic hazard it is assessed which structures and elements are affected and what actions shall be taken. For ground shaking the obvious action is the earthquake-resistant design, however, for important components and smaller structures etc. base isolation or other types of damping mechanisms may be the proper solution.



Figure 2: Tailrace of hydropower plant covered by landslide during the 2008 Wenchuan earthquake in Sichuan Province, China

It is well known that ground shaking affects all structures (above and below ground), whereas the other hazards listed above may only affect entrances, intakes or outlets. However, the Wenchuan earthquake has shown that in the epicentral region, where thousands of rockfalls and slides

occurred, the damage due to rockfall was very serious (Fig. 2). Also some of the dam sites were not accessible for several months.

### **Seismic design criteria for large storage dams**

The following design earthquakes are needed for the seismic design of the different structures and elements of a large dam project (ICOLD 2010):

- **Maximum Credible Earthquake (MCE):** The MCE is the event, which produces the largest ground motion expected at the dam site on the basis of the seismic history and the seismotectonic setup in the region. It is estimated based on deterministic earthquake scenarios. According to ICOLD (2010) the ground motion parameters of the MCE shall be taken as the 84 percentiles (mean plus one standard deviation).
- **Maximum Design Earthquake (MDE):** For large dams the return period of the MDE is taken as 10,000 years. For dams with small or limited damage potential shorter return periods can be specified. The MDE ground motion parameters are estimated based on a probabilistic seismic hazard analysis (PSHA). According to ICOLD (2010) the mean values of the ground motion parameters of the MDE shall be taken. In the case where a single seismic source (fault) contributes mainly to the seismic hazard, uniform hazard spectra can be used for the seismic design. Otherwise, based on the deaggregation of the seismic hazard (magnitude versus focal distance) different scenario earthquakes may be defined.
- **Safety Evaluation Earthquake (SEE):** The SEE is the earthquake ground motion a dam must be able to resist without uncontrolled release of the reservoir. For major dams the SEE can be taken either as the MCE or MDE ground motions discussed above. If it is not possible to make a realistic assessment of the MCE then the SEE shall be at least equal to the MDE. The SEE 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.
- **Design Basis Earthquake (DBE):** The DBE with a return period of 475 years is the reference design earthquake for the appurtenant structures in Europe. The DBE ground motion parameters are estimated based on a PSHA. The mean values of the ground motion parameters of the DBE can be taken.
- **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 (ICOLD 2010). The OBE ground motion parameters are estimated based on a PSHA. The mean values of the ground motion parameters of the OBE can be taken.
- **Construction Earthquake (CE):** The CE is to be used for the design of temporary structures such as cofferdams and takes into account the service life of the temporary structure. There are different methods to calculate this design earthquake. For the temporary diversion facilities a probability of exceedance of 10% is assumed for the design life span of the diversion facilities. Alternatively the return period of the CE of the diversion facilities may be taken as that of the design flood of the river diversion.

MDE, DBE, OBE and CE may be determined by a probabilistic approach (mean values of ground motion parameters are recommended), while for the MCE ground motion deterministic earthquake scenarios are 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.

The different design earthquake ground motions are characterized by the following seismic parameters:

- Peak ground acceleration (PGA) of horizontal and vertical earthquake components.
- Acceleration response spectra of horizontal and vertical earthquake components typically for 5% damping, i.e. uniform hazard spectra for CE, OBE, DBE and MDE obtained from the probabilistic seismic hazard analysis (mean values) and 84 percentile values of acceleration spectra for MCE obtained from the deterministic analysis using different attenuation models.
- Spectrum-compatible acceleration time histories for the horizontal and vertical components of the MCE ground motion determined either from a random process or by scaling of recorded earthquake ground motions. The artificially generated acceleration time histories of the horizontal and vertical earthquake components shall be stochastically independent.

### **Ground motion parameters for underground structures**

For underground structures in rock whose liners are rigidly connected to the rock, no dynamic amplification effects can be expected, i.e. the maximum inertia force corresponds to that of the peak rock acceleration. Inertia effects play mainly a role for the electro-mechanical equipment, structures, cranes, control panels, cable trays etc. located in caverns.

Seismic waves propagating along the tunnel axis or perpendicular to it may cause distortions in the lining. These seismic waves are best characterized by propagating harmonic shear waves. For that purpose the shear displacement and the corresponding wave length must be determined from a seismic hazard analysis. This is in addition to the acceleration ground motion parameters given in the previous section, which are primarily relevant for the electro-mechanical equipment and other installations in tunnels and caverns.

Furthermore, an estimate of the maximum fault movements, the width of the fault zone is needed for the different types of design earthquakes. Fault movements are of main concern for the SEE.

### **Seismic design and performance criteria for underground structures**

For the assessment of the earthquake safety of underground structures, the main parameters of the design basis earthquake (DBE) have to be defined. The DBE may be different for different types of underground structures. If the consequences of a failure do not involve loss of lives, which is the case for hydropower plants then return periods similar to those used in building codes may be selected - but not less. This means that for an underground powerhouse the same seismic design criteria can be used as for a surface powerhouse. The project owner may specify a longer return period for the OBE of the powerhouse and the equipment than that given by ICOLD for the dam body (ICOLD 2010).

Also, as construction of long tunnels may take several years, earthquake action shall also be considered for critical construction phases. For example, the twin tube Bolo highway tunnel, which was under construction during the 1999 Duzce earthquake in Turkey suffered severe damage and a 400 m long part of the tunnel collapsed.

In general, most tunnels and caverns of a hydropower plant can be designed for the DBE using the importance factors given in the earthquake code for structures.

However, in the case of (high-speed) railway tunnels, where the consequences of an earthquake-induced train accident can be very large, the return period of the SEE ground motion may be similar to that used in dam design.

Tighter seismic safety and performance criteria must be applied to safety-relevant elements, i.e. bottom outlets and spillways, which must remain operable after the SEE. Therefore, spillway tunnels as well as tunnels of bottom outlets and their intakes and outlets must be checked and designed for the SEE.

After a strong earthquake the dam has to be inspected, which also includes the inspection of all underground structures.

### **Attenuation of earthquake ground motion with depth**

It is often argued that the intensity of the earthquake ground motion decreases from the earth surface to the location of the underground structure. From the one-dimensional propagation of a displacement wave we know that the displacement at the free surface is twice as high as that of the incident wave. Therefore, a reduction in the ground motion in underground structures is often assumed. However, such ground motion attenuations have to be verified.

Ground motion attenuations may be calculated with a suitable computer program, which takes into account topography, local geology, rock mechanics properties, wave radiation etc. Such analyses may be very demanding especially for strong ground shaking where nonlinear effects may play a role. Depending on the local conditions it is possible that the peak ground acceleration values in a tunnel or cavern exceed those on the rock surface. Therefore, it is prudent to use the same seismic parameters as for the outcropping rock.

### **Fault movements**

Active faults or discontinuities in the rock, which can be activated during strong earthquakes, may cause local damage in a tunnel or cavern. Displacements may occur at such faults and discontinuities. Again, depending on the consequences of fault movements, the return periods of design earthquakes must be determined. In a long tunnel faulting may be the main seismic concern.

Limited fault movements in the range of a few decimeters may be accepted in access tunnels (some road adjustment will be needed) or free-flow tunnels (debris has to be removed and local damage can be repaired).

In lined pressure tunnels fault movements will be of greater concerns as the lining may be damaged and water may seep into the surrounding rock if the internal pressure is higher than the external water pressure. This may cause local hydraulic fracturing of the rock and problems at the surface. Thus, if faulting occurs in a lined pressure tunnel or shaft, the power intake has to be closed and the power plant shut down. The damage must then be repaired.

If faults are well defined in a pressure tunnel then a special lining may be provided, which can cope with the anticipated fault movements. However, such solutions are expensive for large diameter tunnels.



Figure 3: Leakage of existing fissure in bottom gallery of Sefid Rud buttress dam in Iran after the 1990 Manjil earthquake

### **Vulnerability of underground structures to seismic action**

The vulnerability of underground structures in rock can be classified as follows:

1. Underground structures in zones of high seismicity, which have not been designed against earthquakes;
2. Tunnel portals (highly vulnerable; Fig. 4);
3. Tunnels and caverns located in shear zones and potentially active faults;
4. Tunnels and caverns in zones with (tectonically) highly stressed rock formations;
5. Large caverns for underground power plants;
6. Intersections of different tunnels and caverns;
7. Geologically weak zones, which need special attention during excavation;
8. Locations where accidents have occurred during construction and operation;
9. Structures in caverns and non-structural elements in tunnels (ventilation system, drainage, ceiling elements etc.); and
10. Equipment, installations and secondary structures in underground structures.

It has to be assumed that a strong earthquake can trigger failure of unstable rock portions of an underground structure. Therefore, the earthquake resistant design is of particular importance in geologically difficult zones.

The most vulnerable parts of tunnels are the portals, which may be damaged by rockfall or landslides. Such damage has occurred in the epicentral region of the May 12, 2008 Wenchuan earthquake in Sichuan Province, China.



Figure 4: Tunnel portal damaged by rockfall during the 1990 Manjil earthquake

The main earthquake damage in underground structures is spalling of concrete or masonry and cracks in liners.

Serious damage to underground structures of hydropower plants is not known to the author. During the May 12, 2008 Wenchuan earthquake 1803 dams and reservoirs and 403 hydropower plants were damaged to different degrees. Tunnel portals and intake structures were affected by rockfall and landslides (Wieland 2010).

### **Hydrodynamic action in pressure tunnels due to earthquake**

In hydropower plants tunnels or parts of tunnels and shafts may be under hydrostatic pressure. During an earthquake hydrodynamic pressures will be generated in such tunnels and shafts. As the hydrodynamic pressure depends mainly on the fundamental frequency of the water in the pressure system, relatively short tunnels will produce higher hydrodynamic pressures than long tunnels with lengths exceeding say 1 or 2 km (Wieland 2005). For example, plugs in diversion tunnels may be subjected to high hydrodynamic pressures, which exceed the hydrostatic ones. Such short-term forces have to be considered in the design of plugs.

### **Seismic analysis**

As underground structures will move together with the surrounding rock the stresses in the lining can be estimated by shear waves propagating along and vertical to the axis of the tunnel or

cavern. Such simplified analyses are described in the literature (Hashhash et al. 2001, Wang 1993).

More sophisticated analyses include two-dimensional and three-dimensional models of caverns and tunnels. There are hardly any limits to the degree of complexity of a seismic analysis of underground structures in mountainous terrain. It is not the objective of this paper to discuss such dynamic analyses, which can be performed by commercially available, general purpose computer programs.

As the earthquake load case may not be the governing one for tunnels in competent rock a simplified seismic analysis check with propagating waves may be appropriate.

However, dynamic analyses are suitable for the seismic design of the electro-mechanical equipment, cable trays, cabinets etc. installed in caverns.

### **Conceptual design**

Analysis is probably not the best answer to improve the earthquake safety of underground structures.

In the case of caverns the objective is to avoid known active faults or shear zones. This may not be possible for tunnels. Consolidation grouting of fault zones may be the answer in the case of pressure tunnels. Also the provision of joints in the lining may be considered to cope with transverse movements whereas a special movement joint may be needed to cope with axial deformations. Moreover, fault zones can be crossed by a steel penstock, which is supported on free-moving bearings. Finally, in critical zones of very long pressure tunnels additional valves could be considered etc.

At the interface of rock and soil a joint will allow for the relative movement of tunnel segments located in materials with different deformational behavior.

Protective measures will be required at hazardous tunnel portals, and intake and outlet structures. These structural measures are often more effective than sophisticated dynamic analyses.

### **Conclusions**

It is often assumed that underground structures (in rock) are safe against earthquakes and that earthquake action does not have to be considered in the design, and that deep structures are safer than surface structures. Unfortunately none of these assumptions is correct. Today, we know that tunnels and underground structures can be damaged during strong earthquakes. In particular tunnel portals and intakes and outlets of power tunnels are vulnerable to mass movements.

Also deep structures are not necessarily safer than surface structures. If both structures are designed properly against earthquakes then both are equally safe. This applies to most types of structures. However, it is likely that a structure or component located in an underground powerhouse will experience lesser seismic forces than the same structure or component located in a surface powerhouse. However, we know from structural dynamics that such a statement is only correct if the acceleration response spectrum of the surface powerhouse is higher than that of the underground powerhouse for all frequencies.

The main conclusions are as follows:

1. All underground structures have to be checked and designed against earthquakes. In many cases the earthquake load combination will not be the governing one for the design.
2. Earthquakes are multiple hazards and all relevant ones have to be considered in underground structures.
3. Conceptual and structural measures are often more effective than sophisticated dynamic analyses.
4. Equipment and components in caverns have to be designed against earthquakes similar to surface structures.
5. Tunnels for spillways and bottom outlets (including intakes, outlets and valve chambers) must be functional after the safety evaluation earthquake. Therefore, these underground structures have to be designed for higher seismic hazard levels than any other underground structures of hydropower plants.
6. Active fault zones in pressure tunnels need special attention especially when leakage can cause hydrofracturing of the rock.

Earthquake design of underground structures for hydropower plants is still in its infancy. Even 10 years ago hardly any engineer would have considered earthquake action in underground structures in rock. However, for tunnels in soil seismic action had been considered much earlier.

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