COMMISSION INTERNATIONALE
DES GRANDS BARRAGES

VINGT-CINQUIÈME CONGRÈS
DES GRANDS BARRAGES
Stavanger, JUIN 2015

PERFORMANCE CRITERIA FOR ROCKFILL DAMS SUBJECTED TO MULTIPLE SEISMIC HAZARDS(*)

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1. INTRODUCTION

Performance criteria of rockfill embankment dams are based on the response to external loadings, such as external and internal water pressures, gravity forces, and in particular earthquakes, which can be considered as the most severe form of structural loads. These criteria can be quantified and are often expressed as limiting values. Dams whose performance may exceed specified criteria for a certain hazard may be deficient with respect to their safety. Performance assessment, on the other hand requires direct and systematic observation of the dam to loadings and compare these with pre-established design criteria. This paper focusses on the performance of rockfill dams (dams with central impervious core and concrete face rockfill dams) and their response to multiple seismic hazards.

The impact of a seismic hazard depends on the amount of energy released by the earthquake and usually only quakes with a magnitude exceeding about 5.5 are able to cause damage to well-designed and constructed rockfill dams.

(*) *Critères de comportement des barrages en enrochement soumis à des multiple risques sismiques*

Identifying possible seismic hazards in a region of moderate to high seismicity is probably the most important task when selecting a site for the design of a safe storage scheme. Seismic hazards at potential dam sites can vary to a great extent. They depend on the topographical and geological settings, the foundation conditions, the presence of active faults in the region, the distance of the dam site to such active seismic zones, the materials used for the construction of the dam, and the quality of construction.

2. IDENTIFYING SEISMIC HAZARDS AND POSSIBLE ASSOCIATED DAMAGE

2.1 OVERVIEW ON EARTHQUAKE-RELATED HAZARDS AND THEIR IMPACTS ON ROCKFILL DAMS

The identification of seismic hazards bears many uncertainties and therefore requires the cooperation of seismologists and engineering geologists. However, nobody knows in advance when and where the next earthquake will occur and how much energy will be released. The dam, however, has to be designed to withstand the strongest conceivable earthquake ground motion, which according to ICOLD Bulletin 148 (ICOLD, 2014) [1] is the ground motion caused by the Safety Evaluation Earthquake (SEE).

It is based on a 10,000 year return period and requires that safety-relevant components and equipment during and after the SEE must remain fully operable, although minor damage is accepted (e.g. leakage of seals and gates). In no case shall the stability and integrity of the dam structure be impaired and no large quantities of water shall be released from the reservoir.

Seismic hazards caused by strong earthquakes affecting unfavorably the dam body and /or the appurtenant structures can be of the following types:

- Strong ground shaking (causing damage at dam crest and to nearby appurtenant structures).
- Sliding wedge on upstream or downstream dam slopes (may reduce freeboard).
- Movement along discontinuities in the footprint of the dam (e.g. faults, joints, fissures, bedding planes).
- Settlement of dam crest after end of construction.
- Rockfall from nearby high rock wall (causing damage to powerhouse or blockage of spillway and outlet gates).
- Landslides or debris flows (if terrain is saturated) into the reservoir (causing impulse waves which could overtop the dam crest).
- Gaps between earthfill and a concrete face.
- Cracks on the dam crest and in the dam core (caused by differential settlements along an irregular valley profile or along the abutments).

Cracks may lead to internal erosion and eventually to piping in dams without filter protection.

- Loss of strength due to build-up of pore water pressures in dams with shells constructed with poorly compacted sand often associated with liquefaction phenomena.

2.2 STRONG GROUND SHAKING

Strong ground shaking affects the dam site directly. The intensity of shaking depends on the distance to the epicenter of the quake. A nearby quake will not only cause deformations on the dam structure but will also affect the appurtenances. Damages may reach from cracked walls on buildings (powerhouse, office buildings, etc.) to transformers on the switchyard and buckled transmission towers. Also gates for releasing water to downstream may no longer be operable. Cracks can also occur in the pavement of the crest road both in longitudinal and in transverse direction. Appurtenant structures are usually designed according to the local seismic building code taking into account seismic zoning and local soil conditions.

2.3 SLIDING WEDGE ON DAM SLOPE

The formation of a sliding wedge on the dam slope is one of the most frequent hazard encountered with strong earthquakes. It is therefore important to provide the dam with sufficient freeboard, usually at least 6 m. Since ground shaking is being amplified towards the crest, slope failures occur most frequently in this region. With concrete face rockfill dams (CFRD) this failure mode is prevented by the concrete slabs. However, the Zipingpu CFRD lost its downstream crest wall during the Wenchuan 2008 earthquake and concrete slabs overlapped along the horizontal joint between the second and third stage slab. Some of the vertical joints were also damaged. The sliding wedge analysis according to Newmark (1965) [2] is commonly used to estimate the seismic displacement of a soil or rockfill wedge. This is a more rational approach than the use of a seismic coefficient, which will produce conservative slope gradients because factors of safety of less than 1.0 are excluded. The Newmark method enables the factor of safety to become less than 1.0 for a fraction of time during which the sliding body stops to move. It is up to the designer to specify the tolerable amount of the overall displacement. Earthquake damage at the crest of an embankment dam, however, does usually not show a well-defined sliding mass, but rather a combination of slumping and spreading movements.

2.4 MOVEMENTS ALONG DISCONTINUITIES IN FOOTPRINT OF THE DAM

Major active fault zones may occasionally also produce branch or secondary faults which, however, are much shorter in length than the main fault.

If such faults cross the footprint of a proposed dam, it is possible that a strong earthquake may induce a displacement along such a secondary fracture. The question then arises on how much this could be. The magnitude of the displacement has implications on the thickness of the filter zones, because after displacement the thickness of the filter zone should not be less than 50% of the original thickness.

Wang et al. (2009) [3] report on wide-spread surface fracturing within the area affected by the Wenchuan earthquake. These were associated with geohazard locations (landslides, debris flows and potentially unstable slopes).They pointed out that there is much evidence that secondary fractures were also activated by the Wenchuan earthquake. They consider that the widespread effect of the Wenchuan earthquake was enabled by the activation of numerous secondary fractures within the area affected by the generating fault.

2.5 SETTLEMENT OF DAM CREST

An earthquake can provoke settlement of the dam crest, often combined with visible cracks. A comprehensive survey of crest settlements of 69 dams exposed to earthquake ground motions reported by Swaisgood (2003) [4] showed that, not surprisingly, the peak ground acceleration (PGA) has a major influence on the amount of crest settlement. Similarly, crest settlement is also directly related to the surface wave magnitude, Ms, of the foundation rock recorded or estimated at the dam site. An empirical relationship was derived as follows:

$$\text{\%-settlement} = e^{(6.07\ PGA + 0.57\ Ms - 8.0)}$$

where %-settlement is the settlement of the crest of the dam (in m) divided by the height of the dam (in m) plus the thickness of the alluvium (in m) times 100, i.e.:

$$\text{\%-settlement} = \Delta/(DH + AT) \cdot 100$$

where Δ is the crest settlement, DH is the height of the dam, and AT is the thickness of the alluvium.

2.6 GAPS BETWEEN EARTHFILL AND A CONCRETE FACE

Gaps or so-called separation cracks may develop between the earthfill of an embankment and a concrete face (see Figure 1) [5], because the dam fill tends to settle. Contact faces should be smooth with no kink in the face of the concrete. Changes in slope may aggravate crack formation. An even moderate earthquake can contribute to additional settlement and enlarge the width of the already existing separation cracks. Gaps can also form around pipes passing through the embankment. Recommended are pipes encased in concrete founded on a firm foundation. Cutoff collars are not recommended because they preclude the use of rollers to compact the fill around the conduit [5].

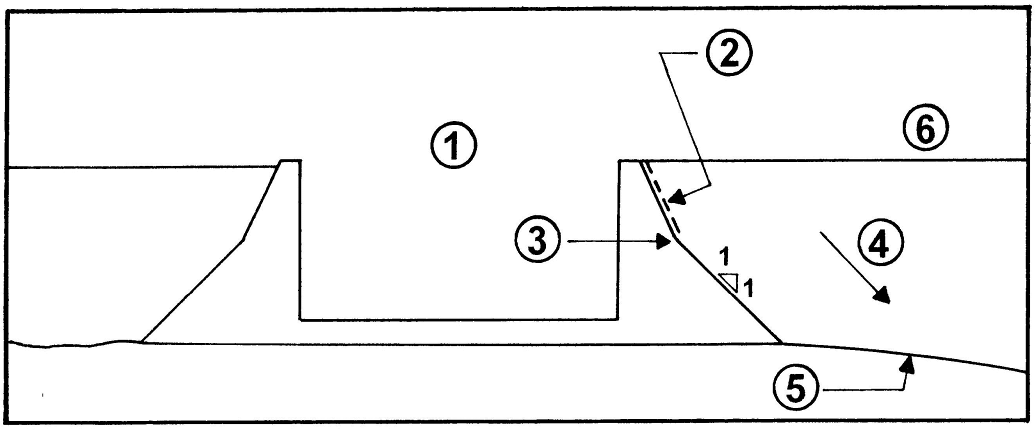


Fig. 1

Crack formation at the contact earthfill/concrete due to dam fill settlement and changing slope of concrete support [5]

Ouverture d'une fissure par suite au contact sol/béton causé par d'un tassement du remblai et par un changement de pente dans l'appui en béton [5]

1	Spillway	1	Evacuateur de crue
2	Potential for gap to form as dam settles	2	Possibilité de formation d'un vide si le barrage se tasse
3	Change in slope	3	Changement de pente
4	Dam fill settles	4	Remblai se tasse
5	Foundation	5	Fondation
6	Dam crest	6	Crête du barrage

2.7 ROCKFALL AND DEBRIS AVALANCHES FROM HIGH ROCK WALLS

In mountainous regions strong earthquakes are able to cause extensive damage through mass movements consisting of rock falls, landslides and debris flows. These may block mountain streams causing landslide lakes which pose further threats to downstream communities. During the 2008 Wenchuan earthquake geo-hazardous events were identified at more than 13,000 locations.

Rockfalls destroyed transmission towers, caused the malfunctioning of gates in run-of-river power plants due to power failure and damaged emergency diesel generators. Blocked gates could not be opened and were overtopped. An important lesson learnt from the wide-spread geo-hazard events is to avoid placing sensitive structures (powerhouses, switchyards, intake towers, etc) next to a high and steep rock wall abutment or otherwise protect these facilities from falling rocks and debris or install these in an underground cavern.

2.8 LANDSLIDES INTO THE RESERVOIR

The sudden plunging of rock- snow or ice masses into the reservoir or onto a landslide lake in the catchment may rise the lake level by a few centimeters. But the resulting impulse waves travelling to the shoreline and towards the dam can cause substantial damage. The most severe event would be an overtopping of the dam. Calculation methods to estimate the height of such waves are available (e.g. Huber 1982, 1984). [6], [7]. Landslides and in particular debris flows also reduce the active storage volume of the reservoir.

2.9 CRACKS ON DAM CREST AND IN DAM CORE

When an embankment dam settles after end of construction, it usually develops some cracks which are visible on the crest.

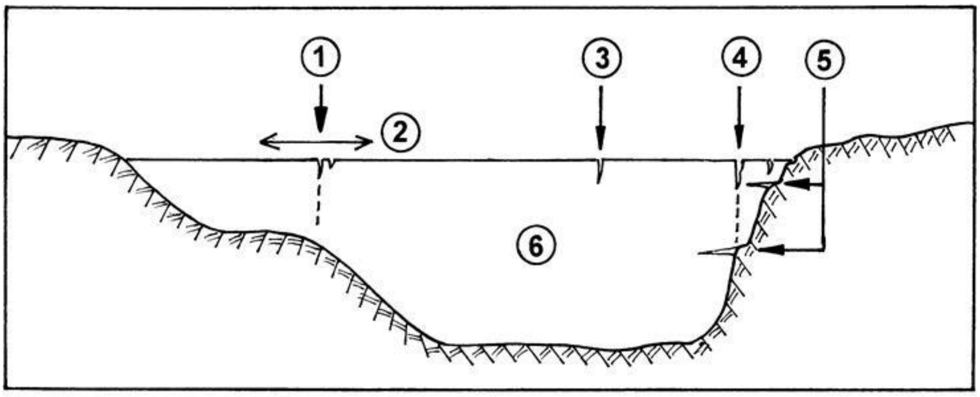


Fig 2
Various possible scenarios leading to the formation of cracks in the dam core [8]
Quelques situations qui pourrissent aboutir à des tassement différentielle et à des fissures dans le noyau [8].

1	Vertical crack due to lateral straining	1	Fissure vertical
2	Lateral straining caused by differential settlement	2	Déformation latérale produite par tassement différentielle
3	Vertical crack formation due to desiccation	3	Fissure verticale produite par dessiccation
4	Vertical crack due to sliding of core along steep abutment wall with steps	4	Fissure vertical dû au glissement du noyau le long d'un appui avec des palier
5	Horizontal cracks due to sliding of core along steep abutment wall with steps (protrusions)	5	Fissures horizontales dû au glissement du noyau le long d'un appui raide avec des paliers
6	Dam core	6	Noyau du barrage

These cracks can be in longitudinal or in transverse direction and also occur without the influence of an earthquake. Longitudinal cracks seem to be more common than transverse cracks, probably because movements in upstream-downstream direction have less confinement. Transverse cracks, however, are more critical as they may pass through the core and open a path for reservoir water to pass through the core. It is therefore important to bring the filter/transition zone to the top of the core such that internal erosion from such cracks can be stopped by the filter zone. Scenarios which are likely to cause cracking are valley profiles or foundation conditions causing differential settlements.

Figures 2 and 3 [5] show some scenarios where cracks can develop in the core. For example, with steps or benches in the valley profile, differential settlements occur due to the different height of the embankment above and below the step. Cracks develop at locations of low stress. When the reservoir is impounded the core of the dam settles and cracks may develop at locations prone to differential settlement. Along very steep abutments (>60°) and also with very high dams the likelihood of horizontal crack formation is enhanced significantly .In addition, low stressed zones may be subject to hydraulic fracturing.

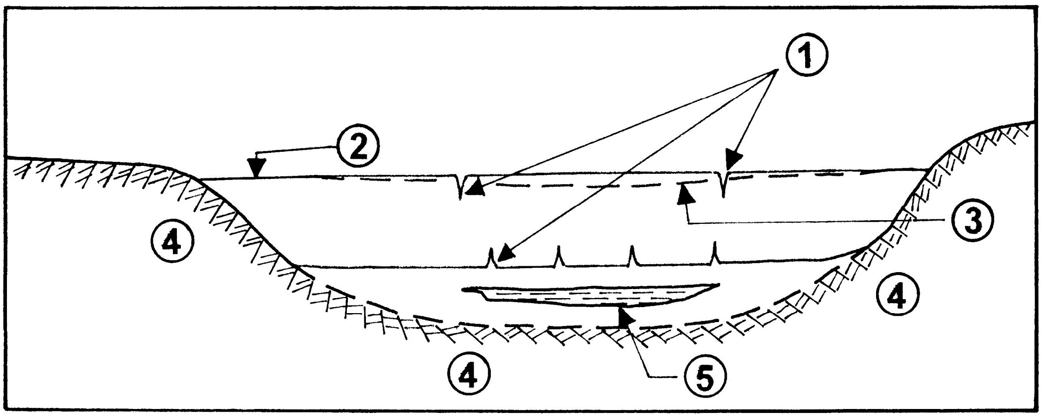


Fig. 3
Crack formation on crest and base of embankment due to differential settlement caused by a soft soil layer [5]
Développement des fissures à la crête et à la base du barrage dû à des tassements différentielles causé par une couche de sol très compressible [5]

1	Potential cracking	1	Possibilité de fissuration
2	Embankment dam crest	2	Crête du barrage en remblai
3	Crest settlement (not to scale)	3	Tassement de la crête
4	Rock	4	Rocher de fondation
5	Very compressible soil layer	5	Couche de sol très compressible

Hydraulic fracturing is a process where the internal pressure is increased in some locations and decreased in others as a result of changes in the internal stress distribution caused by differential settlement. The minor principal stress is reduced to near zero, or to even tensile stress if the core material has sufficient cohesion to withstand tension. If now upon impounding, the water level of the reservoir rises higher than the level with low stress at the upstream core boundary, the water which is at a higher pressure can fracture the low stress zone of the core and the water can enter the core and propagate towards downstream in a concentrated leak opened by a crack. (Sherard, 1985) [9]

High permeability zones, i.e. cracks that transport water through the embankment can be sensed by cone penetration testing (CPT). These water-saturated zones are softer than the surrounding core material. But the holes created by the CPT must be backfilled properly, e.g. with a suitable grout.

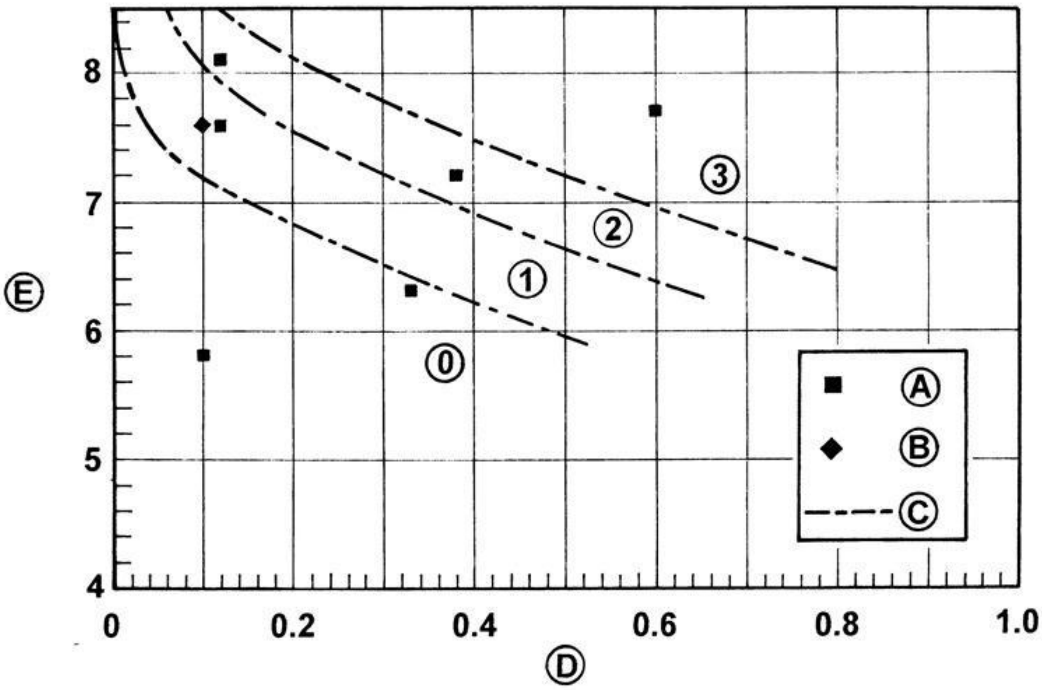
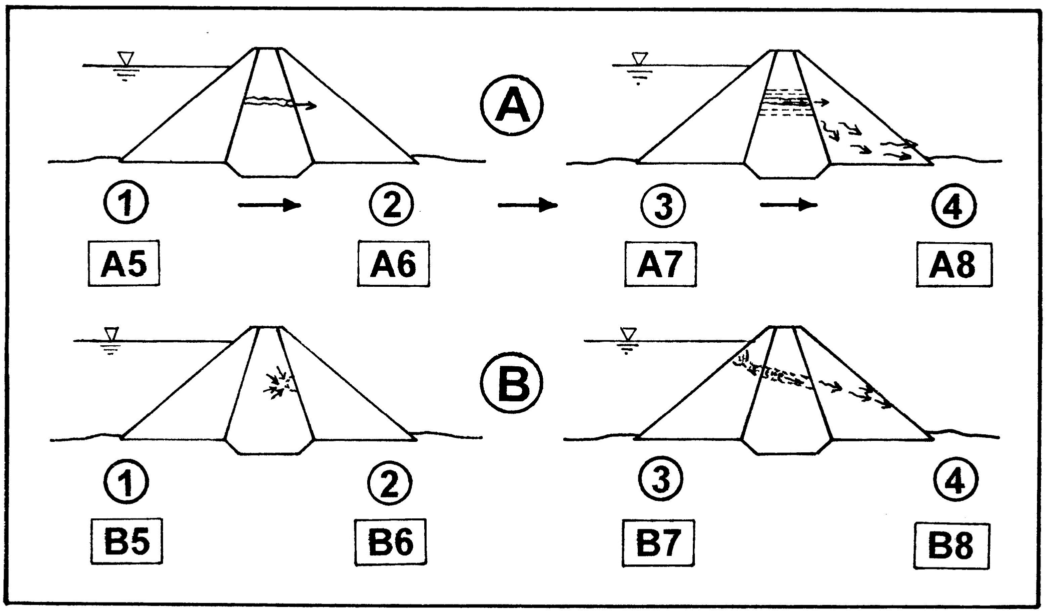


Fig. 4

Earth/rockfill dams where transversal and longitudinal cracks were observed after strong earthquakes plotted in a graph of earthquake magnitude and peak ground acceleration at the dam site and indicating zones of damage [10]

Fissures transversales et horizontales observées à la crête des barrage en enrochement après des tremblement de terre très fort, tracé dans un graphique magnitude envers accélération pointe du sol et indiquant les zones de dommage [10]

A	Cases recorded only transverse cracking	A	Des cas où on a enregistré que des fissures transversales
B	Cases recorded both longitudinal and transverse cracking	B	Des cas où on a enregistré des fissures longitudinales et transversales
C	Damage class contours for earthfill dams 0 no or slight damage 1 minor 2 moderate 3 major	C	Contours des degrès de dommage pour barrages en remblai 0 rien ou très peu de dommage 1 secondaire 2 modéré 3 majeure
D	Foundation peak ground acceleration (g)	D	Accélération pointe du sol (fondation)
E	Earthquake magnitude	E	Magnitude du tremblement de terre



A	**Piping in the embankment initiated by erosion in a concentrated leak**	**A**	**Renard dans l'intérieur du digue initié par l'érosion dans une fuite concentrée**
1	INITIATION	1	INITIATION
2	CONTINUATION	2	CONTINUATION
3	PROGRESSION	3	PROGRESSION
4	BREACH/FAILURE	4	RUPTURE DU DIGUE
A5	Leakage exits on d/s side of core and backward erosion initiates	A5	Les fuites sortent du côté aval du noyeau et l'érosion rétrograde est initié
A6	Continuation of erosion	A6	Continuation de l'érosion
A7	Backward erosion progresses back to the reservoir	A7	Erosion rétrograde
A8	Breach mechanism forms	A8	Formation d'un mechanism de rupture

B	**Piping in the embankment initiated by backward erosion**	**B**	**Renard dans le digue initié par érosion rétrograde**
1	INITIATION	1	INITIATION
2	CONTINUATION	2	CONTINUATION
3	PROGRESSION	3	PROGRESSION
4	BREACH/FAILURE	4	RUPTURE DUBARRAGE
B5	Concentrated leak forms and erosion initiates along walls of crack	B5	Des fuites concentrée se forme et l'érosion se dévelope le long du paroi de la fissure
B6	Continuation of erosion	B6	Continuation de l'érosion
B7	Enlargement of concentrated leak	B7	Agrandissement des fuites concentrées
B8	Breach mechanism forms	B8	Formation d'un mechanism de rupture

Fig. 5
Development of piping by a combination of backward erosion and concentrated leak erosion in the core starting from a horizontal crack in the core[11] .
Développement d'un renard par combinaison d'une érosion type fuite rétrograde et d'une érosion type fuite concentrée [11]

Crack formation under earthquake loading has been studied by Pells & Fell [9]. They showed (Figure 4) that for visible longitudinal cracks to occur the dam needs to experience a magnitude 6.5 or greater earthquake and a PGA greater than 0.15 g for earthfill dam and 0.3 g for earth/rockfill dams. Figure 4 shows 6 locations of earth core/rockfill dams with only transverse cracking and one dam with both transverse and longitudinal cracks.

Cracks in the impervious core may develop into paths for internal erosion (Figure 5) [11]. The erosion mechanisms leading to the formation of a pipe in the dam body and the final breach of the dam will most likely be a combination of backward erosion starting at a crack, followed by concentrated leak erosion. However, the initiation of the erosion process depends on the erosion properties of the materials in the core and the hydraulics of flow in a crack.. Wan & Fell [12] have developed two laboratory tests, namely the Slot Erosion Test (SET) and the Hole Erosion Test (HET) to measure the erosion properties of the soils used in embankment dams. These tests can measure the erosion rate of a soil, but the interpretation of the results still requires expert knowledge.

2.10 EFFECTS OF PORE WATER PRESSURE BUILD-UP

The loss of strength due to build-up of pore water pressures in dams with shells constructed with poorly compacted sand often associated with liquefaction phenomena is a problem that has largely been solved with the understanding of the liquefaction phenomena.

Dam failures have occurred because dam shells were constructed with materials (hydraulically filled sand) which were susceptible to liquefaction.

3. SEISMIC FAILURE MODES OF ROCKFILL DAMS

3.1 POSSIBLE FAILURE MODES DUE TO EARTHQUAKE ACTION

The possible failure modes of earth core rockfill dams caused by strong earthquakes (ground shaking and fault movements causing dam deformations, pore pressure build-up in core materials, etc.) are as follows:

(i) Overtopping of dam when the power plant is shut down or during floods due to (1) malfunction or faulty operation of spillway gates, (2) power failure for spillway gate operation or (3) jamming of gates due to distortions of spillway piers,

(ii) Overtopping due to large seismic settlements of rockfill dam;

(iii) Overtopping due to sliding movements of upstream or downstream slopes,

(iv) Overtopping due to large mass movements into the reservoir close to the dam;
(v) Internal erosion due to (1) formation of cracks in core, and (2) pore pressure build-up in core during strong earthquakes;
(vi) Internal erosion and hydraulic fracturing in ‘tension zones’ in poorly designed and constructed parts of the dam;
(vii) Seepage and erosion along the interface of concrete (intake, spillway structures, concrete dams conduits) with dam;
(viii) Failure of grout curtain, increase in seepage in foundation, dissolution of foundation material causing sinkholes and dam instabilities and deformations;
(ix) Dam failure due to internal erosion caused by movements of faults or discontinuities in footprints of the embankment dam activated by strong earthquakes at nearby faults; and

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Floods, heavy rainfall, mass movements at the dam site and into the reservoir, and failure of spillway gates due to power failure or distortions are other important hazards.

However, the majority of embankment dam failures are often the result of inadequate design and poor construction methods. Therefore, it is very important to ensure the design criteria and the construction of an embankment dam is properly established to reduce the probability of failure.

Furthermore, it has to be kept in mind that due to man-made actions like sabotage, terrorism, and acts of war any dam can be damaged or even destroyed, and there are unknown hazards. Therefore periodic assessments of hazards and associated failure modes are necessary, which shall be part of the dam safety management procedures.

The most critical hazards and failure modes for a dam are those which are unpredictable and occur suddenly. These comprise mainly the earthquake hazard and the man-made hazards such as sabotage, terrorism or acts of war.

3.2 PREVENTIVE MEASURES

In the case of failure modes, whose development can be observed by changes in seep-age, deformations, uplift pressures, progressive deterioration etc., preventive measures are possible to improve the safety. Therefore, dam monitoring and visual inspections are the key elements in avoiding such failure modes.

In earthquake safety checks carried out for embankment dams the following failure modes are of main concern:

- Overtopping of dam due to (1) seismic settlements, (2) power failure for gate operation during floods when the power plant is shut down, or (3) blockage of (damaged or distorted) spillway gates. Possible preventive measures: Dam heightening (top of core should be at elevation of crest of concrete structures, where limited overtopping is accepted), maintenance of gates, gate tests at least once per year, redundant power supply for gate operation, emergency power generator, bottom outlet, etc.

- Internal erosion and hydraulic fracturing in ‘tension zones’. Possible preventive measures: Seepage monitoring, visual inspections.
- Seepage along concrete dam interface. Possible preventive measures: Storage of core material for plugging any leakage, seepage monitoring, deformation measurements, visual inspections.
- Failure of grout curtain, increase in seepage in foundation. Possible preventive measures: Seepage monitoring, chemical analysis of seepage water, maintenance of drainage system, etc.

Movements of faults or discontinuities in the footprints of the embankment dams, which can be activated by strong earthquakes at nearby faults, are important for concrete structures but not critical for rockfill dams with impervious core and wide filter and transition zones.

4. SEISMIC PERFORMANCE CRITERIA FOR ROCKFILL DAMS

4.1 GENERAL CRITERIA

The rather general performance criteria for the dam body and safety-relevant components and equipment given in ICOLD Bulletin 148 [1] can be interpreted as follows:

- Performance of dam body during the Operating Basis Earthquake (OBE): No structural damage (cracks, deformations, leakage etc.), which affect the operation of the dam and the reservoir, is permitted. Minor repairable damage is accepted.
- Performance of dam body during the Safety Evaluation Earthquake (SEE): Structural damage (cracks, deformations, leakage etc.) is 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.
- Performance of safety-relevant components and equipment (gated spillways, bottom outlets) during and after OBE: These components and equipment shall be fully operable after the OBE and therefore should behave elastically during the OBE.
- Safety-relevant components and equipment (gated spillways, bottom outlets) during and after the SEE: These components and equipment 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.

More specific performance criteria may be given for the SEE, e.g. sliding stability safety factors of slopes of greater than 1.0 are required for an SEE with a return period of 2500 years in Germany. Such requirements may be stricter than those given above as during strong ground shaking sliding movements of slopes can be accepted, i.e. sliding safety factors may temporarily drop to less than one during the earthquake. However, in this case the allowable sliding movements would have to be defined based on engineering judgement and the stability of the slope after the earthquake, which may be reduced due to the build-up of pore pressures, must be guaranteed. For that case the safety factors must be larger than 1 taking into account residual strength parameters (zero cohesion) and the effect of pore pressure.

The dynamic sliding stability analyses of slopes of rockfill dams can be done most easily using the Newmark sliding block method. In general the horizontal and vertical earthquake components should be taken into account in two-dimensional models of slopes. The sliding movements depend on (i) the so-called yield acceleration, which is obtained from a pseudo-static stability analysis of the slope and (ii) the duration of ground shaking. Therefore, if sliding movements are important then it is important to use earthquake records with long duration of strong ground shaking.

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The safety-relevant components and equipment are bottom outlets (low level outlets) and gated spillways and all related equipment (mainly gates), motors, hydraulic systems, control panels, power supply, software etc., as it must be possible to regulate and lower the reservoir after the SEE.

As the repair of a damaged dam will need time, it is necessary that after an earthquake a moderate flood equal to about the river diversion flood used during dam construction can still be released safely. Overtopping of embankment dams cannot be accepted, thus after an earthquake the possibly damaged or partly inoperable spillway of an embankment dam must be able to release larger floods than that of a similar concrete dam, which is not vulnerable to overtopping. After the 2008 Wenchuan earthquake several run-of-river power plants were overtopped as the power plants were shut down mainly due to failure of the electric grid and the spillway gates could not be opened due to failure of the (emergency) power supply. No structural damage was inflicted to the overtopped concrete structures.

The main safety criteria for rockfill dams with impervious core for the SEE are as follows:

- loss of freeboard, i.e. after the earthquake the reservoir level shall be below the top of the impervious core of the dam,
- internal erosion, i.e. after the earthquake at least 50% of the initial thickness of the filter and transition zones must be available, and
- the sliding safety factor of slopes (considering build-up of pore pressure and residual strength parameters of embankment materials) shall be larger than 1 after the earthquake.

The second criterion also applies to earth core rockfill dams located on faults or discontinuities in the dam foundation, which can be moving during a strong earthquake. Moreover, at such sites only conservatively designed earth core rockfill dams should be built.

We can conclude that the bottom outlet(s) and the spillway gates must be operable, so a moderate flood can be released safely after the earthquake. It has to be assumed that the power plant will be shut down and water cannot be released through the power waterways. For controlling the water level in the reservoir after a strong earthquake it is not necessary that all openings of a spillway have to be functional.

4.2 PERFORMANCE CRITERIA FOR FAULT MOVEMENTS IN THE FOOTPRINT OF ROCKFILL DAMS

After a displacement, caused by the fault slip, the remaining overlapping filter zone should at least be 2 m. This means that with a design displacement of 1 m one should have a filter of at least 3 m thickness. A safety factor of 1.5 may be added to cover all the uncertainties and one would end up with a filter thickness of about 4.5 m. The filter will have no cracks, because its material has to be perfectly cohesionless. This means that any opening that will be created during the displacement process will collapse immediately. The clay material of the core should be more plastic over the fault zone, so that when it is sheared during the displacement it will not form open cracks which could provoke internal erosion. A horizontal (or strike-slip) displacement of 1 m in an embankment dam foundation can therefore be tolerated without problems.

5. MAIN FEATURES FOR SEISMIC DESIGN OF ROCKFILL DAMS

Dams that perform satisfactorily during strong earthquakes should comply with both (i) conceptual (empirical) criteria, which are mainly based on the observation of the behaviour of embankment dams during strong earthquakes and the behaviour of soils and rockfill under dynamic loadings, and (ii) the results (mainly deformations) of seismic shaking using at least three different sets of earthquake records for the SEE.

The conceptual and constructional criteria recommended by ICOLD for seismic-resistant fill dams are [13]:

- Foundations must be excavated to very dense materials or rock; alternatively the loose foundation materials must be densified, or removed and replaced with highly compacted materials, to guard against liquefaction or strength loss.
- Fill materials, which tend to build up significant pore water pressures during strong shaking must not be used.

- All zones of the embankment must be thoroughly compacted to prevent excessive settlements during an earthquake.
- All embankment dams, and especially homogeneous dams, must have high capacity internal drainage zones to intercept seepage from any transverse cracking caused by earthquakes, and to assure that embankment zones designed to be unsaturated remain so after any event that may have led to cracking.
- Filters must be provided on fractured foundation rock to preclude piping of embankment material into the foundation.
- Wide filter and drain zones must be used.
- The upstream and/or downstream transition zones should be 'self-healing', and of such gradation as to also heal cracking within the core.
- Sufficient freeboard should be provided in order to cover the settlement likely to occur during the earthquake and possible water waves in the reservoir due to mass movements etc.
- Since cracking of the crest is possible, the crest width should be wider than normal to produce longer seepage paths through any transverse cracks that may develop during earthquakes.

The dynamic response of an embankment dam during strong ground shaking is governed by the deformational characteristics of the different soil materials. For large storage dams, the earthquake-induced permanent deformations must be calculated. The calculations of the permanent settlement of large rockfill dams based on dynamic analyses are still very approximate, as most of the dynamic soil tests are usually carried out with maximum aggregate size of less than 5 cm. This is a particular problem for rockfill dams and other dams with large rock aggregates and in dams, where the shell materials, containing coarse rock aggregates, have not been compacted at the time of construction. Poorly compacted rockfill may settle significantly during strong ground shaking but may well withstand strong earthquakes.

6. EXISTING DAMS

The design of a dam, which was considered as safe at the time it was commissioned may not be safe forever. Therefore in view of changes in seismic design and performance criteria, new information on seismicity or increase in risk in the downstream area, several seismic safety assessments will be needed during the long service life of a dam.

The fact that no major dams have failed during earthquakes and that few lives have been lost may give the impression that well-designed dams are safe against earthquakes.

It must be pointed out that both new and existing large storage dams must satisfy today's seismic safety criteria, which are equal for new and existing dams.

7. CONCLUSIONS

In the seismic design and seismic safety assessment of rockfill dams the following items are of main concern:

(1) The seismic hazard is a multi-hazard for most dam projects. Ground shaking is the main hazard considered in all earthquake guidelines for dams and other structures.

(2) Movements of active faults in the footprint of a dam or movements at discontinuities (faults, joints, bedding planes), which can be activated during strong nearby earthquakes, are the most critical seismic hazards for most dam types. If no other site can be selected then a conservatively designed earth core rockfill dam with wide filter and transition zones would be the recommended solution.

(3) As most dams built prior to 1989 when ICOLD has published its seismic design criteria of dams, have not been checked for the SEE ground motion, the earthquake safety of these dams is not known and it must be assumed that a number of them do not satisfy today's seismic safety criteria. Therefore, owners of older dams shall start with the seismic safety checks of their dams.

(4) The earthquake load case has evolved as the critical load case for most large dams even in regions of low to moderate seismicity.

(5) Due to changes in the seismic design criteria or design concepts, new information on seismic hazard or increasing risks in the downstream area, may require to perform several seismic safety checks during the long economical life of a large dam.

(6) Our knowledge on the behaviour of large rockfill dams during strong ground shaking is still limited, therefore, future earthquakes may reveal new features, which may have been overlooked or ignored in the past.

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SUMMARY

In the seismic design and seismic safety evaluation of rockfill dams it is necessary (i) to identify the different types of seismic hazards affecting the dam, i.e. ground shaking, movements of faults or other discontinuities in the footprint of the dam, which can be activated during strong earthquakes, faults in the reservoirs, rockfalls at the dam site and mass movements into the reservoir, and soil liquefaction; (ii) to specify the possible failure modes, i.e. overtopping of the crest, internal erosion, or loss of strength due to pore pressure build-up; and (iii) to define the performance criteria, i.e. the allowable deformations and/or pore pressures etc. The seismic design criteria and the performance criteria cannot be separated. The critical seismic failure modes of earth core rockfill dams and the corresponding performance criteria for the different types of seismic hazards are given and recommendations on dam types and seismic design features are given.

RÉSUMÉ

La conception sismique et lévaluation de la sécurité des barrages en enrochement exige: (i) identifier les différentes types de risques sismiques affectant le barrage, soit les vibrations fortes, les mouvements de failles ou d'autres discontinuités dans l'empreinte du barrage, qui pourraient être réactivés au cours de tremblements de terre forts, les failles dans la retenue, les éboulement de rochers au site du barrage, les glissement de terrain dans la retenue et la liquefaction des sol sableux; (ii) spécification des modèles de rupture, c'est à dire: les deformations permissible, la perte à la résistance au cisaillement dû à l'augmentation des pressions interstitielles et (iii) définir les critères de performance, c'est à dire les deformations permissible et/ou les pressions interstitielles, etc. Les critères de conception sismique et les critères de performance ne peuvent pas être séparés. Les modèles de rupture sismique des barrages en enrochement et les critères de performance correspondantes sont présentés pour les différents types de risques sismiques et des recommandations concernant les types de barrage sont aussi présentées.

Keywords:	Earthquake	Tremblement de terre
	Cracking	Fissuration
	Internal erosion	Érosion interne
	Hydraulic fracture	Fracturation hydraulique
	Rockfill dam	Barrage en enrochement
	Safety criteria	Critères de sécurité