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SEISMIC PERFORMANCE AND ASSESSMENT CRITERIA FOR CONCRETE DAMS

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ABSTRACT

The performance criteria for arch, arch-gravity, gravity and buttress dams subjected to the design basis and maximum credible earthquakes are discussed. For the design of a dam, the total stresses under the combination of static loads and the design basis earthquake shall not exceed the allowable stresses of mass concrete. For the safety evaluation of a dam, the dynamic stability of concrete blocks separated by cracks and/or joints must be guaranteed under the effect of the maximum credible earthquake, i.e. blocks shall neither overturn nor slide or fall down. For that purpose, different types of failure mechanisms of detached concrete blocks have to be studied. In view of the amplification of the dynamic response in the crest region, the hydromechanical equipment located near this region must be designed for the corresponding floor response spectra.

KEYWORDS

Concrete dams; seismic performance criteria; dynamic stability; safety factor.

INTRODUCTION

In structural design, a distinction can be made between deterministic and probabilistic approaches, i.e. the rather old-fashioned allowable stress design and the limit state design of modern structural codes respectively. The two types of limit states are the serviceability limit states and the limit state of ultimate load. The well-known load and resistance factor design, with load and resistance factors calibrated based on the statistical analyses of strength and load distributions (probability density functions), is one way to perform an ultimate load design of a steel or reinforced concrete structure.

In the case of concrete dams, because of the brittle nature of mass concrete, the design is still based on the allowable stress concept. This concept works well, as long as we analyse dams using the beam theory (assumption of plane sections in trial load method) and the seismic coefficient derived from the peak ground acceleration is small, i.e. less than, say, 0.2 g. Most of the existing dams have been designed in this way.

Rather recently, the design philosophy with respect to the earthquake safety of dams has changed. Today it must be shown that a dam with a large damage potential can withstand the vibrations caused by the so-called maximum credible earthquake (MCE) without partial or total collapse. Per definition, the MCE is the largest event that can be expected to affect the dam. This event can be very powerful and can happen close to the dam. One may assume that even in regions of low seismicity, the MCE has a magnitude of, say, 6.5 or more.

Such earthquakes can easily cause peak ground accelerations in the order of 0.5 g. Accordingly, if a linear dynamic analysis is carried out with the MCE, tensile stresses which greatly exceed the tensile strength of mass concrete are calculated. The allowable stress concept is no longer applicable because concrete cracking is expected. Moreover, at re-entrant corners such as along the dam-foundation interface, a stress singularity occurs. If an elastic dam is perfectly bonded to the foundation rock, then tensile stresses occur at the upstream heel of the dam under the full reservoir condition. By refining the finite element mesh in the region of this stress concentration, the computed maximum tensile stresses increase further and exceed the tensile strength of mass concrete even under static loads. Under earthquake action, the tensile stresses in such zones will be even higher. Under these circumstances, the allowable stress concept cannot be used because uneconomical solutions such as post-tensioning, dam thickening, reinforcement, etc. would be necessary to eliminate undesirable tensile stresses. Many dam engineers are still reluctant to abandon the allowable stress concept and suggest the use of an unrealistically high tensile strength of mass concrete or small ground accelerations. The correct way, however, is to consider two levels of earthquakes in line with the limit state design and to define separate performance criteria for the corresponding earthquakes. The procedure to be adopted is discussed in the subsequent sections.

LIMIT STATE CONCEPT FOR EARTHQUAKE LOADS

In line with the limit state concept, the following types of earthquakes are considered:

(i) Serviceability limit state: Design Basis Earthquake (DBE)
The earthquake-resistant design of concrete dams is essentially governed by the serviceability limit state, i.e. under the DBE load combinations, no cracking of concrete is allowed. Accordingly, the design checks are based on a linear-elastic dynamic analysis of the dam-reservoir-foundation system (three-dimensional finite element model) and the allowable stress concept. A design is acceptable when the main principal stresses are within the biaxial strength curve of concrete. Critical stress states are those with pure tensile stresses and combined tension / compression stresses. In the earthquake resistant design and corresponding design checks, there is considerable controversy regarding the dynamic tensile strength of mass concrete which is a function of the uniaxial compressive strength, the rate of load application and the dimensions of the dam (size effect). For a large concrete dam, the dynamic tensile strength is less than 4 MPa (Brühwiler, 1990). Weak zones also exist in dams (grouted vertical contraction joints, horizontal working joints, etc.) with much lower tensile strength. The DBE can be determined probabilistically and can be specified in terms of, say, a 50% probability of not being exceeded in 100 years (ICOLD, 1989). This corresponds to an event with an average return period of 145 years. In building codes, the average return period of the DBE is 475 years; however, in this case, plastic deformations and cracks in ductile steel and reinforced concrete members are accepted, whereas in concrete dams no cracks are accepted.

The allowable stress concept works, except near the edges of the dam-foundation contact and re-entrant corners where stress concentrations with high tensile and/or compressive stresses occur. The stresses obtained from a structural analysis depend on the degree of refinement of the finite element mesh in these zones. One way of dealing with these stress concentrations is to accept a local crack under the DBE. Such cracks are acceptable if they are closed after the earthquake.

(ii) Limit state of ultimate load: Maximum Credible Earthquake (MCE)
For the safety check of a dam, it is necessary that it can withstand the vibrations and movements caused by the MCE. Cracking of concrete is accepted. As pointed out earlier, the peak accelerations of the MCE can be really high, depending on how the MCE and resulting accelerograms at the dam etc. are determined. For the safety check of a dam, it may be assumed that it is cracked, with cracks developing preferably along horizontal and/or vertical construction joints in the dam body and at the dam-foundation contact.

The non-collapse condition can be shown by analysing the dynamic stability (dynamic rocking and sliding movements) of concrete blocks detached by cracks. Similarly, the stability of wedges in the foundation rock has to be analysed. For these checks, relatively simple rigid body models (so-called kinematic models) of the detached concrete blocks or wedges in the foundation can be used. It is well known that in a cracked structure most of the deformation is due to the deformations of the crack and not the elastic deformation of the intact concrete. The procedure to be followed is similar to that proposed by Newmark for the computation of the dynamic slope stability of embankments. From the computational point of view, the analysis models for the safety check of a dam are much less complex than the finite element models used for dam design.

The term of MCE is somewhat ambiguous. In practice, there are great problems in estimating the magnitude, the location and the ground motions caused by the MCE. In the absence of any potentially active faults, the MCE may have to be determined probabilistically in terms of an average return period or simply by specifying a maximum ground motion at the site. There is considerable uncertainty and also subjectivity in the estimate of the MCE.

It may be noted that the MCE used in dam design is much stronger than the DBE specified in building codes. In ductile structures it is assumed that the ductility of the structural members will prevent failure during an earthquake exceeding the DBE, whereas in a concrete dam the MCE is the upper limit which cannot be exceeded. Therefore, if a dam is stable for the MCE, it is safe in a deterministic sense.

PERFORMANCE CRITERIA OF CONCRETE DAMS

At present, the following two performance criteria apply for concrete dams:

(i) DBE: sum of static and dynamic stresses must be within allowable biaxial stress curve, i.e. no structural cracks are accepted (the deformations in concrete dams due to full water load and DBE are usually small and do not govern the design).

(ii) MCE:
structural cracks are accepted; however, these shall not lead to local failure of detached concrete blocks or collapse of the dam.
- stability of the foundation (wedges in rock and dam) must be guaranteed.
- equipment and installations for the drawdown of the reservoir after an earthquake as well as spillways must function after an earthquake; damage is accepted in redundant facilities.

We must also realise that an earthquake constitutes a multiple hazard. The vibrational effects discussed in this paper are only one of the several features. The worst case for safety is an active fault passing through the foundation of an arch dam. Such problems have to be dealt with separately.

Regarding the optimum performance of a dam during an earthquake, the following criteria must be satisfied:

(i) Stiffness: The dam must have adequate stiffness to limit the static and dynamic deflections; the stiffness also affects the dam eigenfrequencies and the inertia forces caused by an earthquake.

(ii) Strength: Sufficient strength is required to prevent local damage (cracking of mass concrete) during small earthquakes (≤DBE).

(iii) Ductility: As mass concrete is a brittle material, the ductility of a dam represents the ability of detached blocks to undergo inelastic rocking and sliding movements with energy dissipation by Coulomb friction along the crack/joint surfaces. Because of the size of detached blocks, movements up to one to two metres could still be acceptable under the MCE as long as the stability of the block is ensured.

(iv) Stability: The dynamic stability of detached concrete blocks (rocking and sliding motions) as well as wedges in the foundation under the effect of the MCE must be ensured. Movements of wedges in the foundation of arch and arch-gravity dams are detrimental to the safety. Because of the large amplification of the peak ground acceleration from the base of the dam to the crest, which can reach values of 7, the pseudostatic safety factor of a detached concrete block for sliding and overturning can drop below 1 under the MCE, especially in the central upper portion of arch dams. Therefore, a dynamic stability analysis must be carried out.

Historically, the performance criteria for dams and other structures have evolved from the observation of damage and/or experimental investigations. Numerical calculations are also useful in this context; however, the structural models have usually been calibrated with observational data.

Up to now, only a few large concrete dams exist which were damaged during an earthquake (National Research Council, 1990), such as Koyna gravity dam (India, 1967), Hsinfengkiang buttress dam (China, 1962), Sefid Rud buttress dam (Iran, 1990) and Pacoima arch dam (USA, 1994). The main lessons learnt from these incidents show that earthquakes can cause peak ground accelerations which are several times as large as the design values, and that well-built dams can survive very strong earthquake vibrations. From the damage observed at these dams, no new seismic performance criteria have evolved. However, the earthquake loads have increased and the analysis models have been refined to better describe the actual behaviour of a dam during an earthquake.

Two concrete dams have experienced exceptionally high vibrations (Fig. 1), i.e.:

- Lower Crystal Springs Dam: 42 m high curved gravity dam, made up of interlocked concrete blocks; reservoir was full at the time of 1906 San Francisco earthquake (M = 8.3); dam located at a distance of about 350 m from an active fault.
- Sefid Rud Dam; 103 m high buttress dam; reservoir was nearly full at the time of the 1990 Manjil earthquake (M = 7.5); dam located in Northwest Iran at a distance of less than one kilometre from an active fault.

The first of the above dams was undamaged, the second suffered severe cracking in the top portion. Although several detached cantilevers could be observed, there were no signs that any sizeable sliding or rocking motions occurred during the strong ground shaking (joint movements were estimated at less than 2 cm). This is mainly due to the stabilising effect of the friction force at joint interfaces.

Typical crack patterns of two arch dam models subjected to earthquake loads applied in the laboratory are shown in Fig. 2. In both dams, cracks appear in the central upper portion of the dam. Although these dam models were monolithic in nature, they show almost vertical and horizontal cracks. In the existing dams, the vertical cracks will most likely follow the contraction joints. The available observations and studies with the performance of cracked dams during strong ground shaking show that cracks and joints in a massive dam do not necessarily lead to an unsafe state. Therefore in a seismic safety assessment, the engineer must look carefully into the post-cracking behaviour of dam. Cracks are dangerous when they form unstable wedges. The cracks, however, cause a reduction in the eigenfrequencies of a dam and an increase in static and dynamic deflections.

DYNAMIC STRENGTH OF MASS CONCRETE AND CONCRETE CRACKING

The dynamic strength properties of mass concrete have been discussed by Brühwiler (1990). As the tensile strength of concrete depends on the compressive strength, the compressive strength may be varied within the dam such that the requested tensile strength can be achieved for the relevant DBE load combinations.

Under the MCE, cracking of mass concrete is expected in the central upper portion of arch, arch-gravity, gravity and buttress dams. Cracks may also develop along the upstream heel of the dam. In this case, the reservoir depth plays an important role as the water pressure in an existing (static) crack may lead to accelerated crack propagation. Along the upstream dam face, the critical crack length is roughly inversely proportional to the water depth, i.e. at the heel of a deep reservoir, one may expect longer cracks than in a less deep one. Cracking is also governed by the fracture toughness of concrete which is higher for mass concrete than for ordinary concrete with smaller aggregates. Observations suggest that cracks in the upper portion of a dam will completely pass through the dam body.

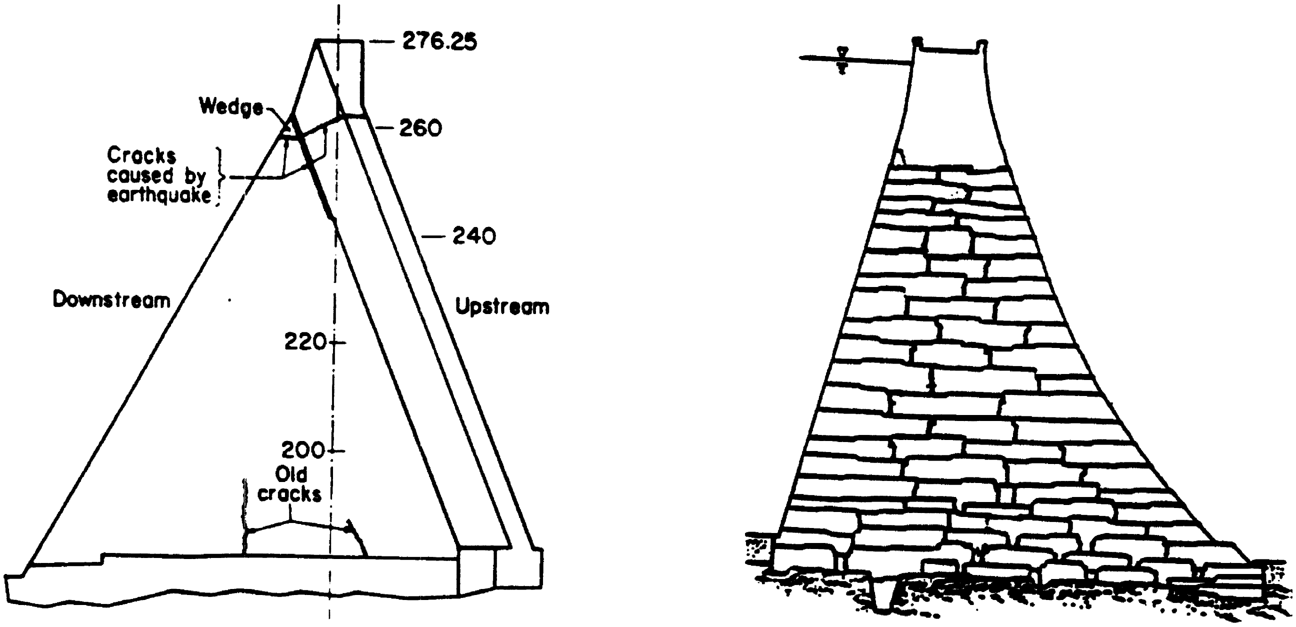

Fig. 1 Typical earthquake damage in tallest nmonolith of Sefid Rud buttress dam and typical cross-section of Lower Crystal Springs gravity dam consisting of interlocking concrete blocks.

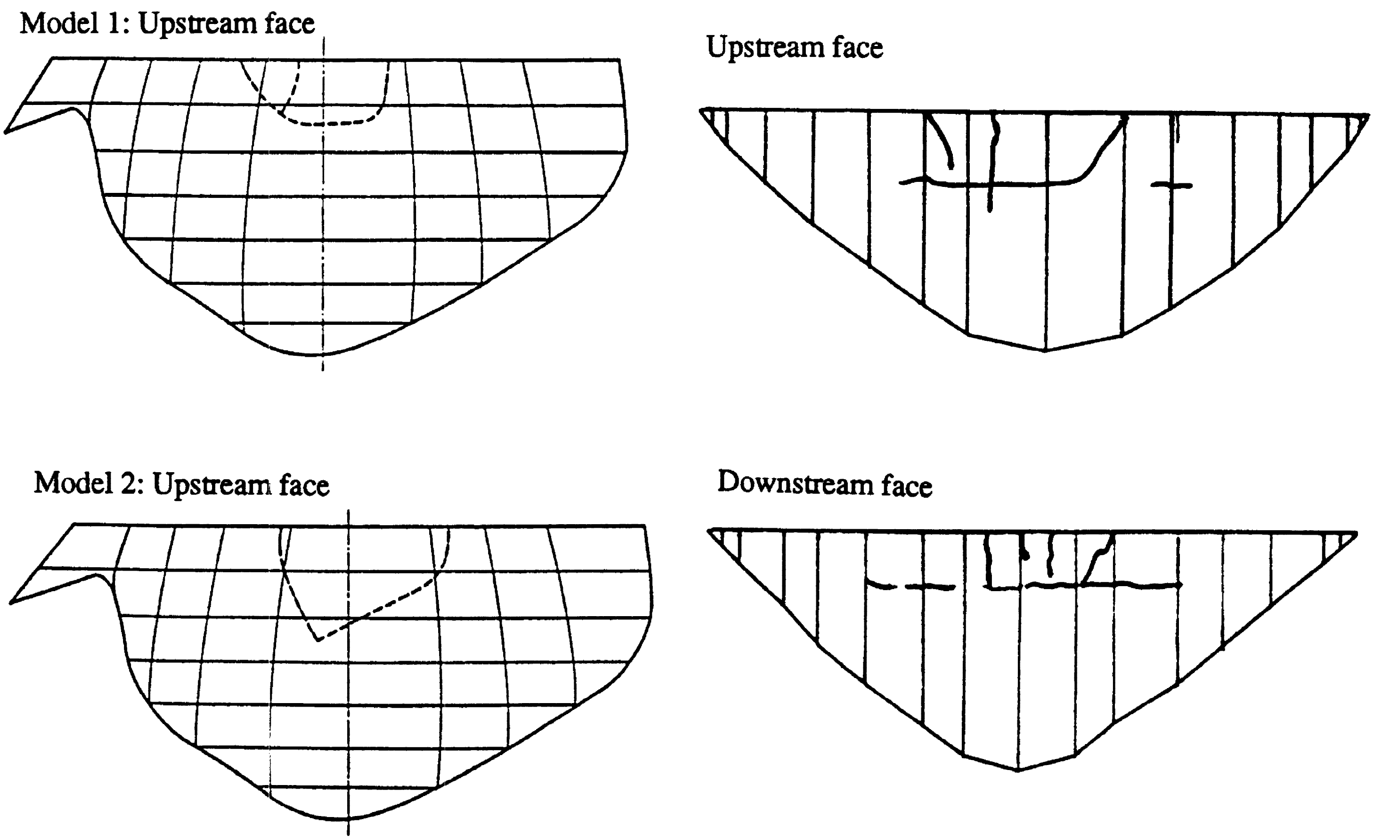

Fig. 2 Crack patterns in arch dams models caused by simulated earthquake loads laboratory (left: Karun I arch dam; right: Ertan arch dam)

In view of the stagewise construction of concrete dams with (regular) horizontal lift joints, cracks will form mainly along horizontal planes and the grouted vertical construction joints. In roller compacted concrete dams, horizontal cracks can be expected.

GLOBAL STRUCTURAL PERFORMANCE

In terms of global behaviour, clear structural systems are recommended, i.e. gravity dams shall carry the load by cantilever action and arch dams by a combination of arch and cantilever action. Numerical studies (Malla and Wieland, 1995) have shown that in an arch dam relatively small friction forces are necessary to prevent relative movements of cantilevers separated by friction joints. In gravity dams with a slight curvature in plan or gravity dams in relatively narrow valleys, axial forces along the dam axis are produced by the water load and/or the deformations in the foundation rock due to dead load of the dam. These forces are generally sufficient to prevent joint sliding. Thus the earthquake behaviour of a gravity dam can be represented more realistically by a three-dimensional analysis than by a traditional plane strain analysis. The three-dimensional behaviour leads to changes in the stress distribution, a reduction in the crest deflection, higher eigenfrequencies and other mode shapes.

Many concrete structures which possess pronounced structural asymmetry have suffered severe damage during earthquakes, i.e. when the centre of stiffness and mass do not coincide. Similar behaviour is expected for concrete dams, i.e. a symmetric dam can be expected to perform much better than a highly unsymmetric one during an earthquake. It is also easier to properly understand and predict the earthquake behavi9our of a symmetric dam and predict its behaviour.

Because of symmetry, the symmetric modes will be excited by the vertical and along-canyon earthquake components, and the asymmetric modes by the cross-canyon component. By contrast, in an arch dam with irregular shape, each mode can be excited by all components of the ground motion. Therefore, a qualitative prediction of the earthquake behaviour of the dam is not possible and one has to rely on by computer simulation. Moreover, the stresses are more likely to occur in an unsymmetric dam.

STRUCTURAL INTEGRITY

During the MCE, cracks may be formed in a dam. To improve the structural integrity of a cracked dam and to prevent independent movement of detached concrete blocks, the following solutions are possible:

(i) Antiseismic belt along the crest of an arch dam: This belt consists of a layer of reinforcing steel bars and restrains relative rocking movements of adjacent cantilevers. There are two dams with such a device, i.e. Rapel arch dam in Chile (110 m high) and Sir arch dam in Turkey (120 m high) (Carrere, 1990). Reinforcement of the crest is an acceptable solution for thin arch dams, especially in view of the high amplification of the ground acceleration in the crest region.

(iii) Post-tensioning of cantilevers: This method is suitable for gravity dams and has been employed for the repair of Sefid Rud buttress dam described earlier (Wieland, 1994).

From the point of view of earthquake safety, dam sections with re-entrant corners shall be avoided, the crest thickness in arch dams shall be relatively large, and high arch stresses in the rock abutment shall be reduced by filets and the overall stiffness of the dam shall be high (small static deflections due to full reservoir load and high eigenfrequency). The stiffening of the crest leads to a significant drop in seismic stresses in the central upper portion of the arch dams and a thick dam ensures that the dynamic stability of detached concrete blocks is taken care of. Structural integrity is impaired when cracks form unstable wedges in a dam or when the concrete disintegrates under repeated load cycles.

PERFORMANCE CRITERIA FOR EQUIPMENT AND APPURTENANT STRUCTURES

All equipment installed on the dam crest is subjected to very large accelerations in up/downstream direction under seismic excitement. For example, during the 1994 Northridge earthquake, peak accelerations of up to

2.5 g were measured along the dam crest. For the design of the equipment, appropriate floor response spectra have to be used. Equipment with fundamental eigenfrequency close to that of the dam will be subjected to extremely high seismic forces, i.e. inertia forces which are up 7 times as high as if the equipment would be installed on ground. This affects mainly central crest spillways. A corresponding example is shown in Fig. 3 for the proposed 125 m high Salman Farsi arch-gravity dam in Iran, where the central crest spillway must be designed for very high spectral accelerations (Wieland et al., 1995). Frequency tuning of the affected equipment beyond 10 Hz is recommended for high dams.

For the appurtenant structures, such as power house and intake structure, the design can be carried out in accordance with established structural codes. However, it is important that for structural elements located on the dam, the floor response spectra on the dam be used and not those given in the codes. Some judgement is necessary to adjust the response spectra for the differences in the average return period of the DBE used in dam design and that given in structural codes.

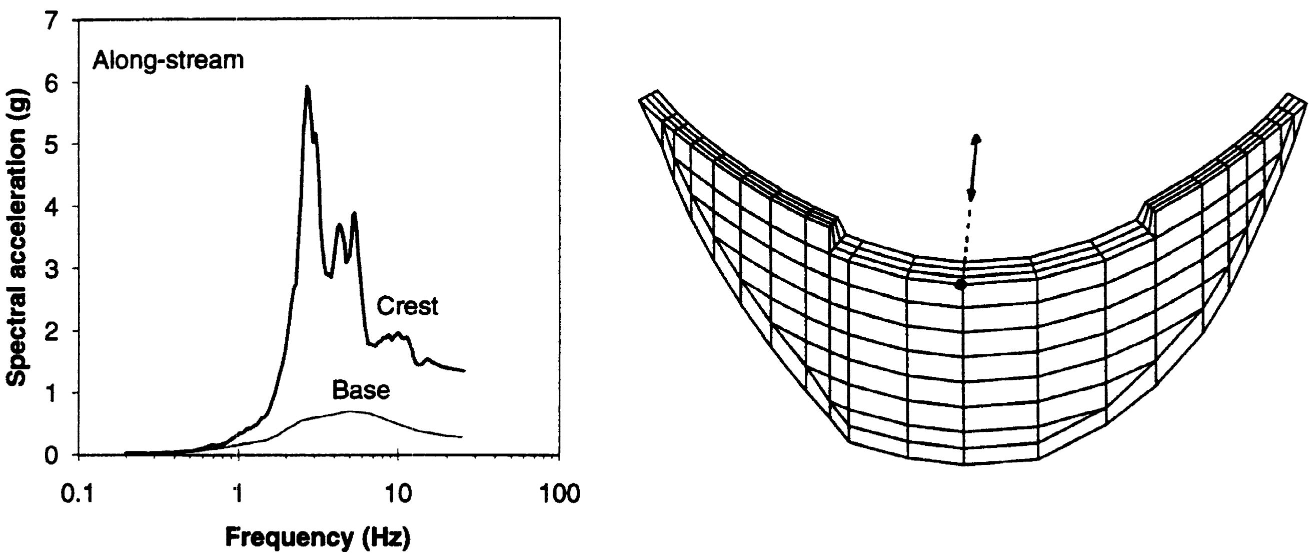

Fig. 3 Floor response spectrum of absolute acceleration in up/downstream direction for 5% damping for dam crest and base input spectrum for DBE of Salman Farsi arch-gravity dam (reservoir compressible with energy-absorbing far end)

SAFETY FACTORS

The dam owners and operators are usually not familiar with the performance criteria of dams. In the absence of any codes and regulations, the engineer has to fill this gap. It is certainly wise to refer to modern structural codes and the performance criteria used in similar dam projects.

The performance criteria are usually limits which shall not be exceeded. The engineer must show in his design that these limits can be kept, with a certain margin to allow for uncertainties. The uncertainties are represented by a safety factor. The following error bounds may be estimated for the earthquake analysis of concrete dams:

- error from estimate of earthquake ground motion (DBE, MCE): ca. 30% (or more)
- error from structural modelling and analysis: (dam-reservoir-foundation model, size of FE model, numerical integration) ca. 20% (higher errors in re-entrant corner zones)
- error from material modelling: (material properties of concrete and rock; structural damping) ca. 20%

As these errors are statistically independent, they do not have to be added. To account for the above uncertainties, a safety factor of 1.4 is appropriate for the DBE.

For the MCE, a slightly reduced safety factor of 1.3 is appropriate for the dynamic stability analysis of detached concrete blocks. In that case, using a rigid body model of a detached cantilever, the main uncertainty is due to the estimate of the earthquake ground motion.

The response spectra for the DBE and MCE shall be the average spectra (e.g. average values of the spectrum amplification factors and peak values of ground motions). In the safety checks for the DBE, the allowable concrete stresses can be expressed in terms of a fractile of the concrete strength. For MCE calculations, average values of material properties shall be used. In order to avoid an over conservative approach, rather than simply accumulating safety factors, sensitivity studies are recommended.

CONCLUSIONS

There are no codes and regulations which are universally applicable for the earthquake-resistant design of concrete dams. Performance criteria must, therefore, be discussed on a case-by-case basis.

Two performance criteria are applicable to concrete dams which comply with the limit state design concept, i.e.:

- design level (DBE): no structural cracks are accepted
- safety level (MCE): structural cracks are accepted; however, the dynamic stability of the dam and detached concrete blocks must be guaranteed.

To achieve these goals, the dam types and shapes have to be optimised together with the required concrete strength within the dam.

In the design and safety checks, safety factors of 1.4 and 1.3, respectively, are recommended to cope with the uncertainties in the earthquake ground motion, structural modelling and analysis, and in modelling the static and dynamic material properties.

All equipment located on a dam must be designed using the corresponding floor response spectra. Acceleration amplification factors of up to 7 have to be expected in the central crest area of arch and gravity dams.

Dam deformations are of no concern for the DBE; however, for the MCE, the rocking and sliding deformations of detached blocks have to be limited. These limits vary from dam to dam and must be determined based on the size of the detached block. Block movements can be restrained effectively by an antiseismic belt located in the crest region.

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