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EARTHQUAKE SAFETY AND EARTHQUAKE-RESISTANT DESIGN OF LARGE CONCRETE DAMS

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ABSTRACT

The state-of-the-art in earthquake safety assessment and the earthquake-resistant design of large concrete arch dams in zones of high seismicity is presented on the basis of several dams investigated by the author in Iran. The basic criteria, design parameters and analysis procedures for the optimum earthquake-resistant design and safety evaluation of large concrete dams are given, i.e.

- Design: Design basis earthquake; finite element modelling of dam-reservoir-foundation system;
- Safety: Maximum credible earthquake; rigid body modelling of detached cantilever blocks of dam formed by cracks and wedges in the dam foundation.

KEYWORDS

Seismic hazard; earthquake safety; earthquake-resistant design; concrete arch and gravity dams; dynamic analysis of dams.

INTRODUCTION

A number of developments have led to a gradual change in the aseismic design philosophy and seismic safety assessment of concrete dams. Firstly, the engineers have realised that during strong earthquakes, peak ground accelerations can be produced which by far exceed the design accelerations used in a pseudostatic analysis. Thus today ICOLD has adopted an approach based on two levels of earthquakes similar to the one used in the nuclear industry, i.e. the design basis earthquake (DBE) and the maximum credible earthquake (MCE). Secondly, developments in structural modelling, numerical methods and computer hardware allow the dynamic analysis of complex three-dimensional dam-reservoir-foundation systems with tens of thousands of degrees of freedom. The refined finite element models of dams with (20 node) solid elements give a better insight into the stresses within arch dams as the trial load analysis. In particular, at re-entrant corners and other locations with stress concentrations, the stresses increase with an increase in mesh refinement in that zone. In the old days when rather coarse meshes were used, these stress concentrations did not appear to the extent they do now. Thirdly, research in the field of strength of mass concrete has shown that the dynamic tensile strength of mass concrete in large dams depends on the strain rate and the size effect, i.e. the tensile strength decreases with increasing size of a dam. Dynamic tensile strengths of typical mass concrete beyond approximately 4 MPa can hardly be justified at present.

The consequences of these developments are: earthquakes with moderate peak accelerations in the range of 0.2 g to 0.3 g can locally cause tensile stresses in a large dam which exceed the strength of mass concrete in the tension or combined tension-compression range of a biaxial strength curve. These facts call for a new approach in the earthquake-resistant design of new dams and the safety evaluation of existing dams.

The introduction of new design concepts is generally slow in the case of concrete dams, as a number of unresolved problems and questions remain. Firstly, no large concrete dam has actually failed during an earthquake and there are only about five concrete dams world-wide which have been damaged by strong earthquakes. Secondly, the dynamic tensile strength of mass concrete is still an unknown. What happens when the tensile stresses in a dam exceed the strength of mass concrete? For example, based on a linear-elastic analysis, it may be concluded that during the 1994 Northridge earthquake, the maximum tensile stresses within the Pacoima arch dam were larger than the corresponding strength of mass concrete. The peak ground acceleration at the base of the dam was about 0.5 g, a value which may be representative for the MCE in many parts of the world. Except for joint movements at the thrust block and some cracks in that zone, no damage was reported similar to the one to be expected based on the results of a conventional stress analysis, i.e. high stresses in the central upper portion of the dam and along the dam-foundation contact zone.

The limited experience with the earthquake performance of large concrete dams also shows that after the development of the first cracks, the dams still have substantial reserves. In that sense, it is not reasonable to reject a design because the allowable stress criterion cannot be satisfied at all points within the dam (and the foundation rock). Especially at re-entrant corners, high local stresses are acceptable as long as the maximum crack width is small and the cracks are closed after the earthquake.

Observations also reveal that cracks occur mainly along horizontal and vertical construction joints where concrete strength is reduced. These cracks prevent the other parts of the dam from further cracking in the case of strong earthquakes.

In the past, assuming a seismic coefficient of 0.1 g, the earthquake load case was a straightforward one, which hardly had any impact on the design of a concrete dam. Today, assuming more realistic ground accelerations for the DBE and the MCE, the earthquake load becomes the dominant load.

In the subsequent parts, the state-of-the-art in the earthquake-resistant design and seismic safety evaluation of concrete dams is presented from the point of view of the practising engineer. As progress and state of knowledge in the various disciplines (seismic hazard analysis; finite element modelling and dynamic analysis of dam-reservoir-foundation systems; material technology of mass concrete and rock; fracture mechanics; assessment criteria for seismic performance of dams, etc.) relevant for the evaluation of the earthquake safety of dams differ significantly, a well-balanced approach is necessary in which all disciplines are integrated. Completeness of a comprehensive assessment is more important than focusing on specific phenomena.

METHODOLOGY FOR SEISMIC SAFETY ASSESSMENT AND ASEISMIC DESIGN

The main items relevant for the seismic safety assessment of existing concrete dams are given below:

a) Seismic hazard analysis (estimation of DBE and MCE in terms of accelerograms or response spectra);

b) Structural modelling of dam-reservoir-foundation systems and calibration of model;

c) Mechanical properties of mass concrete and rock under earthquake loadings;

d) Modelling of post-cracking behaviour;

e) Observational data on the earthquake behaviour of large concrete dams and model tests; and

f) Performance criteria for arch dams under earthquake action.

From the above, item (b) is well-advanced and various computer programs exist which allow the prediction of the earthquake behaviour of a dam in the linear range when the ground excitation is known. The other disciplines are less developed. Until recently, the main performance criterion was the allowable tensile stress of mass concrete. In addition, stability criteria against sliding and overturning had to be satisfied. Today, as mentioned earlier, two types of earthquake actions are considered. Under the DBE (relevant for the design), no structural damage is accepted in a concrete dam, whereas under the MCE, no critical damage can be tolerated, i.e. no catastrophic release of water from the reservoir. Accordingly, the stability of the dam and the foundation must be guaranteed and no failure of any parts of the dam body shall take place.

For the earthquake-resistant design, the following two criteria have to be verified:

a) DBE: By means of a dynamic stress analysis, it has to be checked that the maximum static and dynamic tensile stresses are below the dynamic tensile strength of mass concrete. The stress analysis is carried out using a three-dimensional finite element model of the dam-reservoir-foundation system.

b) MCE: No local or global failure is accepted which leads to uncontrolled release of water from the reservoir. Concrete cracking is accepted. To prove the dynamic stability of detached concrete blocks separated by cracks and contraction joints, relatively simple rigid body models with rocking and sliding degrees of freedom can be used.

For the analysis of various large dams in Iran, the DBE has a 50% probability of being exceeded in 100 years and the MCE is an event with an average return period of approximately 2000 years. Based on the results of comprehensive seismic safety studies reported by Lotfi et a. (1995), Wieland and Lotfi (1994), Wieland (1994) and Wieland et al. (1995), the following conclusions can be drawn:

- The DBE load case governs the earthquake-resistant design.
- Although the MCE has peak ground accelerations which are about twice as high as those of the DBE, the dynamic stability of detached concrete block is not a serious problem when the dam satisfies the DBE performance criteria.

STRUCTURAL MODELLING

For the prediction of the earthquake safety, sophisticated nonlinear computer models have been developed which account for cracking of concrete (smeared cracks, discrete cracks). However, these methods are still in the research and development phase and are not yet ready for practical application.

The main assumptions for the earthquake analyses of three-dimensional concrete dams performed by consulting firms at present are:

a) Incompressible reservoir (added mass) or compressible reservoir with energy absorbing boundaries;

b) Linear-elastic material properties of mass concrete and rock;

c) Massless, homogeneous foundation (kinematic dam-foundation interaction);

d) Structural damping (viscous damping);

e) Linear time history analysis with spectrum-compatible accelerograms for DBE and MCE (three components of ground motion); and

f) No spatial variation of earthquake ground motions.

Dynamic foundation-reservoir interaction effects are usually neglected for arch dams. Using these assumptions, the dynamic analysis becomes straightforward, and major problems regarding the radiation damping in the foundation, and problems in connection with the introduction of the earthquake excitation into the structural model can be eliminated. In view of the uncertainties involved in the estimation of the earthquake ground motion, the dynamic strength properties of mass concrete, the foundation rock and the grouted construction joints, the above assumptions for the earthquake analysis are justified.

EARTHQUAKE-RESISTANT DESIGN AND DYNAMIC OPTIMISATION OF DAM

Which dam type is most suitable to resist strong earthquakes and what is its shape? The guiding principles which apply almost universally are:

- symmetry and simplicity
- uniform distribution of stiffness and mass;
- uniform strength;
- not too elongated in plan (to minimise the effect of non-uniform ground motion);
- no stress concentrations;
- ductility and damping; and
- high stiffness in crest region.

Among these principles, the last two need further explanation. The ductility of an unreinforced concrete dam is represented by its post-cracking behaviour and covers the range between the full development of cracks and the limits of dynamic stability of detached concrete blocks. Therefore, to achieve ductility, brittle shear failure mechanisms have to be avoided in the dam-foundation contact zone. As a matter of fact, cracks may not be detrimental to the earthquake safety of a dam. The 57 m high Lower Crystal Springs gravity dam, whose crest is slightly curved in plan and which is located very close to the San Andreas fault, survived the powerful 1906 San Francisco earthquake with no damage. The dam is made of a large number of interlocking concrete blocks. The friction in the joints and the block interlock prevented joint movements. A similar mechanism is expected for the detached cantilevers of an arch or arch-gravity dam.

The other point is the high stiffness in the crest region of an arch dam which is necessary to reduce the deflections and accelerations in that zone and to increase the frequencies of the lowest modes of vibrations. It is well known from shell theory that a strong shell can be achieved when the applied loads are carried by membrane forces and not in bending. Large bending stresses and corresponding deflections occur along the free boundary of a shell, i.e. along the crest in an arch dam. The stiffening of the crest is, therefore, the most efficient means of changing the dynamic properties of a dam. Accordingly, the location of a large crest spillway will also affect the fundamental mode shapes considerably.

Dynamic shape optimisation is essentially a trial and error procedure combined with engineering judgement. The optimum dam shape obtained for static loads can be used as the reference shape for dynamic optimisation.

In the case of the 125 m high Salman Farsi arch-gravity dam (Wieland et al., 1995), the crest region was stiffened. The location of the spillway, which was initially determined based on hydraulic considerations only, was shifted. Filets were provided along the abutments to reduce the stress concentrations along the dam-foundation contact, and the thickness profile of the cantilevers was changed. The result of this optimisation was very satisfactory as the maximum dynamic tensile stresses in the central upper portion of the dam could be decreased by roughly 50% as compared to the original dam.

Many concrete structures which possess pronounced structural asymmetry have suffered severe damage during earthquakes, i.e. when the centre of rigidity and the centre of mass do not coincide. The dam designer is well-advised to note this lesson. Otherwise, he may end up in extensive dynamic analyses. Sophisticated analyses will not make a dam with a highly asymmetric shape to perform well during an earthquake. Therefore, dynamic optimisation must start at the right time in the planning process.

To sum up: a well-designed dam like any other structure subject to earthquake loads must have the following ingredients:

a) Stiffness: The dam must have adequate stiffness to limit the static and dynamic deflections; the stiffness also affects the dam eigenfrequencies and the inertial forces mobilised by an earthquake.

b) Strength: Adequate strength is required to avoid cracks during small earthquakes ($\leq$ DBE).

c) 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.

d) 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.

DYNAMIC MATERIAL PROPERTIES

The following material properties for mass concrete and rock must be known (minimum requirement):

- mass density and elastic properties
- static and dynamic tensile strength
- structural damping

In most cases, except for the mass density, these material properties are not known accurately. Therefore sensitivity analyses have to be performed where the main material parameters are varied within limits which have either been determined experimentally or have been taken from reference projects or the literature.

For design purposes (DBE), all of the above material properties play some role; however, for the assessment of the dynamic stability of detached blocks (MCE), the elastic properties and strength properties can be disregarded.

For design purposes, the following factors affecting the tensile strength of concrete can be accounted for:

- relationship between tensile strength (f_t)and compressive strength (f_c'), e.g. $f_t = 0.29 \mid f_c' \mid ^{0.67}$ (f_t and f_c' in MPa);
- age effect on concrete strength (it may be assumed that the DBE occurs when the dam has reached about one third of the design life);
- strain rate effect (under rapid loading, the tensile strength increases);
- size effect (the tensile strength depends on the fracture toughness of mass concrete and the thickness of the dam).

If the size effect is considered, the dynamic tensile strength of mass concrete in relatively thick arch-gravity dams drops to below 3 to 4 MPa. Research into the dynamic tensile strength of mass concrete and fracture properties is still in progress.

As far as the elastic rock properties are concerned, they play a minor role on the stresses in thin arch dams.

The damping ratios to be assumed for the dynamic analyses with DBE and MCE ground excitations are not known. From small-amplitude vibration tests, we know that the damping ratios of large arch dams can be of the order of 1% even under full reservoir condition. Damping ratios of 5 and 10% have been used for the DBE and MCE respectively. High energy absorption occurs in the crack processing zones; however, once a crack is fully developed, energy absorption is mainly due to friction. Therefore, if no relative movement in a crack or joint takes place (e.g. rocking motion of free-standing detached concrete block), the damping ratio of the MCE load case can even be less than that used for the DBE. As the damping ratio is the most important parameter which affects the dynamic response of a dam, this factor must be selected with great care and the results of a dynamic analysis must be interpreted taking the strong influence of the damping ratio into account.

LINEAR EARTHQUAKE ANALYSIS (DBE)

If water compressibility in the reservoir and wave radiation are considered, then a direct time history analysis is carried out. There exist several general and special purpose computer programs which can be utilised. The main problem is to select and present the results in a way such that the designer can draw appropriate conclusions. The accuracy of the results is usually not a problem in a linear analysis as long as the finite element models analysed by different programs are the same. Results of a linear earthquake analysis of a 125 m high arch-gravity dam are shown in Fig. 1.

Remarkable for most concrete dams is the fact that the acceleration in up/downstream direction is amplified by a factor of up to 5 to 7 from the base to the crest. This is mainly due to the fact that the lowest dam eigenfrequencies are within the range of the predominant frequencies of the earthquake (ca. 2 to 7 Hz). In a three-dimensional dam model with almost symmetrical shape, the maximum earthquake stresses will be located in the central upper portion of the dam and along the dam-foundation contact zone. In the latter, because of a stress concentration, the computed earthquake stresses can reach very high values, which depend on the size of the finite element mesh in that region.

NONLINEAR EARTHQUAKE ANALYSIS (MCE)

An earthquake with a peak ground acceleration in the order of 0.5 g will cause tensile stresses exceeding the tensile strength of mass concrete. As a consequence, cracks will appear as discussed by Wieland (1994, 1996). The dynamic behaviour of a cracked dam is quite different from that of a solid dam. As a matter of fact, most of the deformations of a cracked dam will be due to deformations of the crack. The elastic deformations of the portions separated by cracks or joints are negligible. Accordingly, the behaviour of a fully cracked dam is similar to that of interconnected rigid bodies with rocking and sliding degrees of freedom. In the case of the MCE, it must be shown that these rigid bodies are stable from the dynamic point of view, i.e. detached concrete blocks shall neither fall into the reservoir (arch dam) nor downstream (straight gravity dam). Simple rigid body models which represent detached concrete blocks have been studied by Lotfi et al. (1993) and Malla et al. (1996). The rocking eigenfrequency of a rigid rectangular cantilever of width b and height h can be taken as $f = 0.306 \times \sqrt{gb/(h\delta)}$, where $g = 9.81$ m/s^2 and δ is the maximum deflection at the top, i.e. for $b/h = 0.4$ and $\delta = 0.1$ m, we obtain $f = 1.92$ Hz.

As the grouted vertical contraction joints in arch dams have smaller strength than the mass concrete, it is of interest to know how much the joints will actually open. For that purpose, an idealised arch dam with four vertical joints was analysed as shown in Fig. 2. The loads applied in sequence were the static water load (full reservoir) followed by a time-varying pseudostatic earthquake load with inertial forces according to the first symmetric mode of the dam (Malla and Wieland, 1995). The spectral acceleration was gradually increased from 2.5 g to 4 g and finally to 6.5 g, i.e. values which are larger than those due to the MCE. If a friction coefficient of 1.0 is assumed in the vertical joints, then the maximum joint movement of adjacent cantilevers will be less than 600 mm in the upstream direction for a spectral acceleration of 6.5 g. These computations have essentially confirmed what has been observed at the Sefid Rud buttress dam mentioned earlier, i.e. relative joint movements are restrained effectively by the friction forces in the joints. Thus by analysing the dynamic stability of detached concrete blocks (disregarding joint friction), the dynamic deformations of these blocks are greatly overestimated.

HYDROMECHANICAL EQUIPMENT

Because of the large amplification of the acceleration response in the crest region of most concrete dams, it is necessary to design any equipment located in this region for the corresponding floor response spectra. From Fig. 1 we can note that it may become uneconomical to install equipment with eigenfrequencies in the range of the maximum spectral amplifications. High or low tuning of the equipment would be the right solution.

Moreover, the hydrodynamic actions on gates and valves must also be determined based on the proper floor response spectra. The correct seismic analysis and design of the equipment are jvery important as these elements have usually not been studied as thoroughly as the dam body. A seismic coefficient of 0.1 g is still widely used!

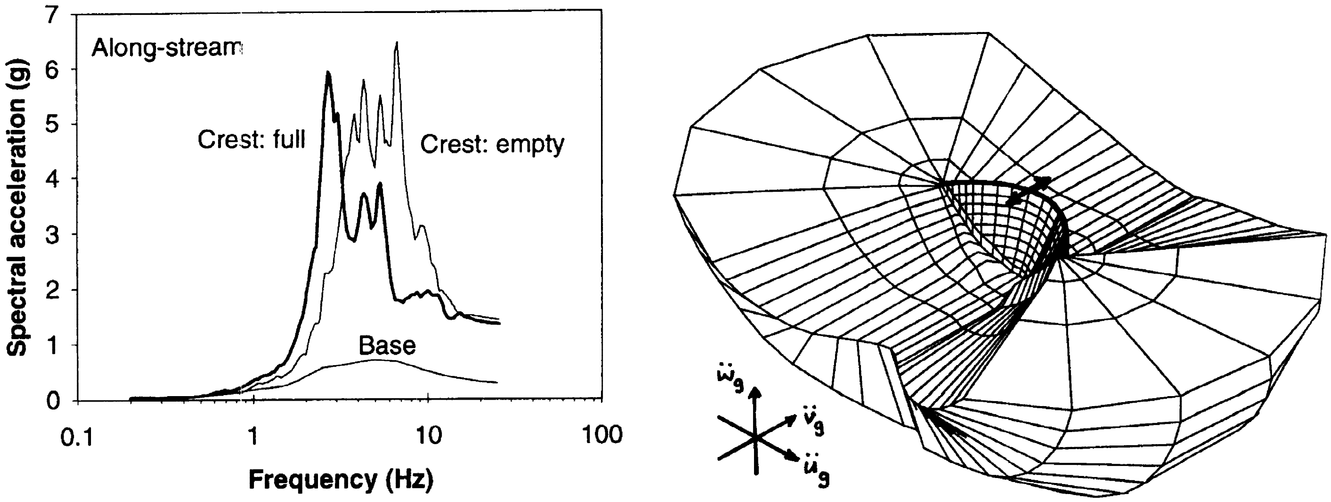

Fig. 1 Comparison of floor response spectra of absolute acceleration in up/downstream direction at dam crest of Salman Farsi arch gravity dam for full compressible reservoir with energy absorption at the far end and empty reservoir (damping ratio: 5%; base input spectrum is given for reference; dam height 125 m)

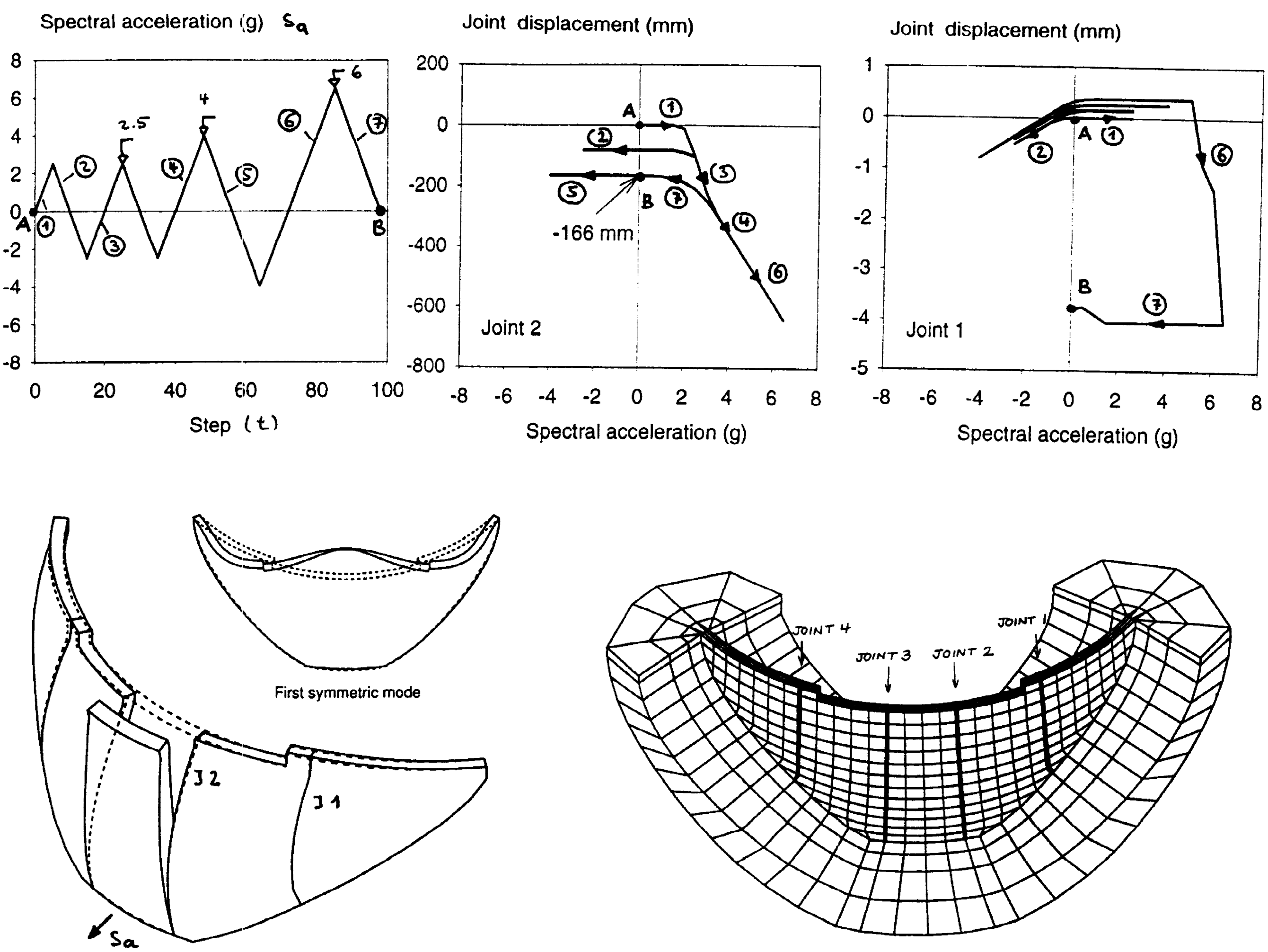

Fig. 2 Joint opening due to time-varying pseudostatic earthquake load in accordance with first symmetric mode of Talvacchia arch dam (cyclic loading; dam modelled with four friction joints; dam height 77 m)

CONCLUSIONS

Based on the studies carried out in connection with the design and seismic safety evaluation of a number of large dams in zones of high seismicity, the following conclusions can be drawn:

- Clear concepts exist for the earthquake-resistant design of dams for DBE and MCE loads.
- Well-designed dams analysed pseudostatically with a low seismic coefficient can usually withstand the MCE without local or global collapse.
- Under earthquake actions, concrete dams generally behave as three-dimensional structures. Two-dimensional behaviour is applicable if the vertical contraction joints are left open.
- The zones of highest earthquake stresses are in the central crest region and the dam-foundation contact zone.
- To reduce earthquake stresses and to improve the earthquake behaviour of arch dams, the crest region has to be strengthened.
- Symmetric dam shapes are superior to strongly asymmetric ones.
- A dam with horizontal and vertical cracks has substantial safety reserves in the case of strong earthquake shaking.
- Arch dams are vulnerable to fault movements in the foundation.

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