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Influence of cracking on the earthquake response of concrete gravity dams with reservoir

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ABSTRACT: The formation and growth of cracks in a concrete gravity dam may influence significantly the earthquake response of a dam. A reliable estimation of the safety of these structures depends essentially on the prediction of the dynamics of crack formation. This study examines the influence of the compressibility of water, the strain-softening of mass concrete and the aggregate-interlock of rough crack surfaces on the crack formation.

The dam is modelled by finite elements. The reservoir is composed of two parts: a finite part modelled by boundary elements adjacent to the dam and a semi-infinite part represented by an analytical solution. A discrete crack approach is used to model the tensile cracking. The strain-softening is based on the fictitious-crack concept. The aggregate-interlock model allows a realistic simulation of the effects due to the roughness of crack surfaces.

The results show that the formation of cracks and consequently the response of gravity dams are significantly influenced by the aforementioned mechanisms. Since the influence of strain-softening is small, brittle crack propagation is expected to dominate in dams.

1 INTRODUCTION

In concrete gravity dams, severe earthquake ground motion may induce stress fields which exceed the tensile strength of concrete. As a consequence cracks may form and propagate, weakening parts of the structure. This may influence the dynamic behaviour of gravity dams. Thus, the response of a cracked structure will differ significantly from that of an uncracked one. An accurate prediction of the dynamics of crack formation is essential for a reliable estimation of the safety of dams subjected to earthquake ground motion.

The proper modelling of the crack propagation in concrete is an arduous task. Several models have been proposed so far for the nonlinear dynamic analysis of concrete gravity dams. Most of them are based on the smeared crack approach with various modifications (see El-Aidi and Hall (1989), Vargas-Loli and Fenves (1989)). However, a discrete crack approach seems to have some advantages compared to a smeared crack model, although the implementation is more involved. Detailed models for strain-softening and aggregate-interlock can be built in straightforwardly (Skrikerud and Bachmann (1986), Feltrin, Wepf and Bachmann (1990)).

These models use a pure tensile stress criterion for the onset of the formation of cracks. This may be interpreted as retrogressive compared to the modern fracture mechanic concepts for the description of crack propagation. But unfortunately these kinds of criterions lack the flexibility of a local tensile stress criterion. They require a too detailed finite element partitioning in the neighbourhood of the crack tips in order to be applied advantageously in a nonlinear dynamic analysis of a large structure like a gravity dam. However, from a theoretical point of view, the use of a tensile stress criterion may be considered as unsatisfactory.

Furthermore the response of a concrete gravity dam is also determined to a large extent by the adjacent reservoir and foundation rock (Fenves and Chopra (1984)). As a consequence these substructures have to be appropriately included into the model. However, the spatial extension of both substructures are very large compared to the size of a dam. In order to obtain a manageable problem, the size of the discretized portion of the reservoir and foundation rock must be restricted to an area of the same order as the size of the dam.

At these arbitrary boundaries the dynamic behaviour of the excluded portion of the reservoir and foundation rock must be taken into account in order to avoid unphysical wave reflections. This requires a time domain formulation of non-reflecting boundary conditions. Several approximations have been pro-

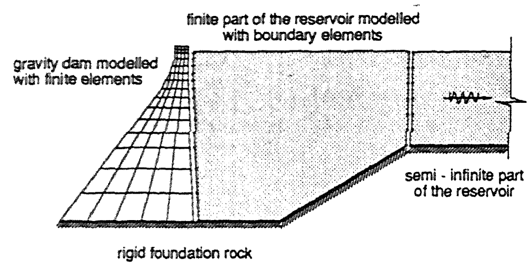

Figure 1: Dam-reservoir model

posed by different authors (see the review paper by Kausel (1989)). Under normal conditions, however, these kinds of models are not completely transparent for outgoing waves. In the reservoir model described in the next section, the non-discretised portion of the reservoir is fully integrated. Non-physical wave reflections are thus avoided.

2 MODEL

Since the model has been described in more detail elsewhere (Feltrin, Wepf and Bachmann (1990)), only its most essential concepts and components will be summarized in this section.

As represented by Figure 1, the dam-reservoir system is modelled along a two-dimensional cross-section in a plane perpendicular to the dam axis. The dam is discretised by planar four-node isoparametric finite elements. The semi-infinite reservoir is conceptually divided into two parts: the near field and the far field. The near field is discretised by boundary elements and may assume an arbitrary shape. The far field is modelled by a semi-infinite channel of constant depth. The foundation rock is assumed to be rigid. Thus the influence of the soil flexibility has been neglected.

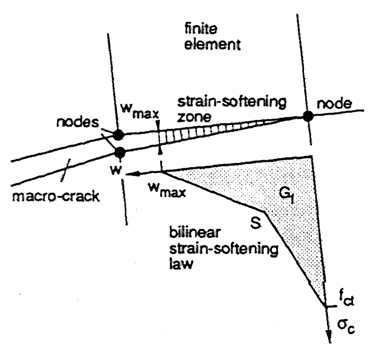

Figure 2: Strain-softening model based on the fictitious crack concept

2.1 Crack model

The modelling of cracks is based on a discrete crack concept. The crack is represented by a crack element which is introduced into the finite element mesh. As a consequence, the mesh topology changes gradually with each new crack by addition of new nodes and new elements.

The cracking mechanism is subdivided into three phases:

- crack formation and growth
- micro-crack phase with strain softening (fictitious crack concept)
- macro-crack phase with aggregate-interlock

Crack propagation is controlled by a biaxial stress-failure criterion for concrete. If the state of stress at an integration point of a finite element reaches the failure criterion, a crack element is introduced into the mesh perpendicular to the direction of the largest principal tensile stress.

The modelling of the micro-crack phase is based on the fictitious crack concept proposed by Hillerborg, Modeer and Petersen (1976). The residual tensile stresses acting across the crack are assumed to be a bilinear function of the fictitious crack width (see Figure 2). The area under the softening relation equals the fracture energy G_f. A major advantage of the fictitious crack concept is the explicit introduction of the fracture energy as a model parameter. Thus, in contrast to a smeared crack approach, the fracture energy is insensitive to the size of finite elements (Vargas-Loli and Fenves 1989).

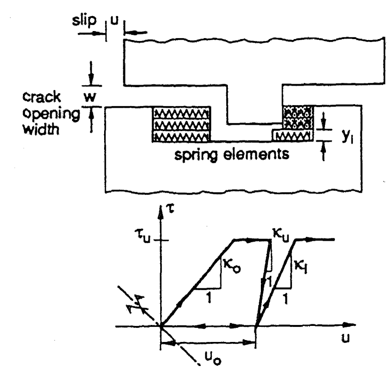

Figure 3: Aggregate-interlock model

By definition, the strain softening phase ends when the opening width w exceeds the maximum opening width w_{max} (see Figure 2) over the full length of a crack element.

From this state onwards a macro-crack is considered to be fully developed and the transfer of forces across the crack will be determined by the aggregate-interlock model (Skrikerud and Bachmann (1986)).

The roughness of the crack surface, the force transfer across the crack and the dilatancy effects are modelled by a set of parallel springs. Each spring is characterized by an action height y and a nonlinear shear stress-displacement relationship (see Figure 3). Dilatancy effects are included by assuming proportionality between crack-opening forces and shear forces.

A set of closure conditions allows the full transfer of compression forces across the crack even when not fully closed. This accounts for the mismatch of displaced rough crack surfaces.

2.2 Fluid-structure interaction model

The dam-reservoir interaction is based on a generalized mass matrix which defines the coupling relations in space and time of the hydrodynamic water pressure and of the dam accelerations on the dam-reservoir interface (Wepf, Wolf and Bachmann (1988)).

The fluid is assumed to be compressible and nonviscous. The fluid motion is irrotational and restricted to small amplitudes.

Neglecting the influence of surface waves, the pressure at the fluid surface vanishes. This boundary condition is included into the fundamental solution. Thus the discretisation by boundary elements of the reservoir surface is avoided. Since the foundation rock is assumed to be rigid, the waves are completely reflected at this boundary.

Using the analytical solution of a semi-infinite channel of constant depth the global behaviour for outgoing waves of the far field reservoir part can be reduced to a boundary condition at the interface between the reservoir parts. Thus at this interface the waves are not reflected.

For the assembly of the generalized mass matrix the problem is formulated in the frequency domain and the frequency dependent entries of the matrix are computed using the boundary element technique. The matrix is then condensed to the degree of freedom along the dam-reservoir interface and finally transformed to the time domain.

In the time domain the coupling between the pressure field and the acceleration field at the dam-reservoir interface is expressed by convolution integrals. The interaction forces are computed evaluating these integrals.

3 STUDY ON A CONCRETE GRAVITY DAM

An analysis is performed on the tallest non-overflow monolith of the Pine Flat Dam. The dam is located in Kern County, California, USA. The monolith has a base width of 95.8 m and a height of 121.9 m. The water level is assumed at 4.8 m below the dam crest.

The reservoir is assumed to be semi-infinite and of constant depth. The shape of the dam monolith with the adopted finite element mesh and the boundary element discretisation of the finite reservoir part is given in Figure 4.

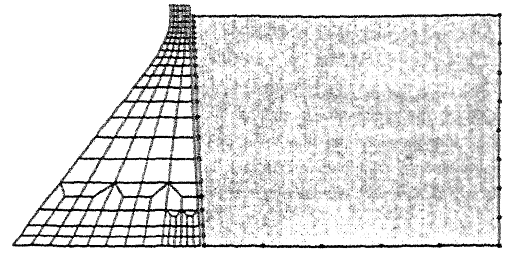

Figure 4: Discretisation of the Pine Flat Dam and of the adjacent finite reservoir part

The concrete is assumed to have a mass density of 2480 kg/m^3, a modulus of elasticity of $22.4 \cdot 10^3$ MPa, a Poisson ratio of 0.2 and a tensile strength of 2.5 MPa. The mass and stiffness proportional damping coefficients are fitted to produce a damping ratio of 6.5 % at the fundamental vibration mode of the uncracked dam with empty reservoir ($f_{dam} = 3.17$ Hz).

The fracture energy G_f of the mass concrete is assumed as 275 Nm^{-1}. The parameters of the aggregate-interlock model are defined to give a maximum surface roughness of 3.8 cm and a maximum shear stress of 4.8 MPa.

The water has a density of 1000 kgm^{-3} and a pressure wave velocity of 1440 ms^{-1}. The frequency of the fundamental vibration mode of the reservoir is 3.07 Hz.

As ground motion, the Taft Lincoln School Tunnel S69E record from the 1952 Kern County earthquake is used. All computations are performed applying the horizontal component of the earthquake ground motion in upstream direction. The earthquake peak ground acceleration is 1.8 ms^{-2}.

The initial state of stress and strain of the uncracked dam is computed from gravity and hydrostatic loads.

3.1 Influence of fluid-structure interaction

As shown by Fenves and Chopra (1984), the interaction between the dam and the reservoir has a significant effect on the response of a concrete gravity dam. In the frequency domain, the coupling relations between the hydrodynamic pressure field and the acceleration of the dam at the dam-reservoir interface are complex and frequency dependent. This characteristic can be interpreted as a frequency dependent mass and viscoelastic damper.

A first major consequence of these relationship is a considerable lengthening of the vibration periods of the dam: The fundamental frequency of the Pine Flat Dam drops from 3.17 Hz to 2.5 Hz.

A second effect is the supplementary damping

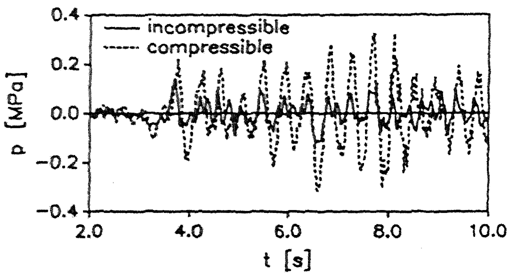

Figure 5: Hydrodynamic pressure p at 80 m depth for incompressible and compressible fluid

mechanism due to the energy flux coupled to the wave propagation from the near field to the far field. This effect is a genuine consequence of the compressibility of the fluid. An incompressible fluid leads to a lengthening of the vibration period but doesn't allow any kind of geometrical damping since no wave propagation occurs.

Even for a compressible fluid a considerable energy flux towards the far field occurs only if the predominant frequency in the system is greater than the cut-off frequency of the first eigenmode of the reservoir. Unfortunately this is not the case for a typical concrete gravity dam even at full reservoir. The full reservoir of the Pine-Flat Dam has a first natural frequency of 3.07 Hz. As a consequence, the additional damping due to the energy flux is small and does not contribute significantly to the reduction of the dam response.

This fact, however, does not support the thesis that an added mass approach (incompressible fluid) is a sufficient device for the modelling of the fluid-structure interaction. As shown in Figure 5, the time variation of the hydrodynamic pressure resulting from the added mass approach corresponds to the earthquake ground motion multiplied by an appropriate scaling factor. In contrast, the hydrodynamic pressure variation of the compressible fluid reflects the inherent predominant vibration frequency of the coupled system (2.5 Hz). Furthermore, the amplitudes of the pressure show remarkable differences too. For a compressible fluid, the pressure peaks are higher than for an incompressible fluid. This is due to the resonant response amplification of the reservoir for frequencies in the neighbourhood of the cut-off frequency of the first eigenmode ($f_1 = 3.07$ Hz).

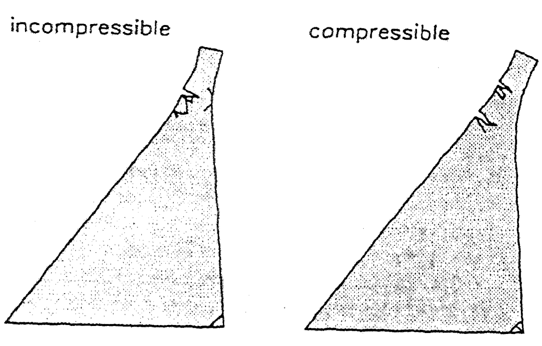

Figure 6: Crack pattern at 20 seconds for incompressible and compressible fluid

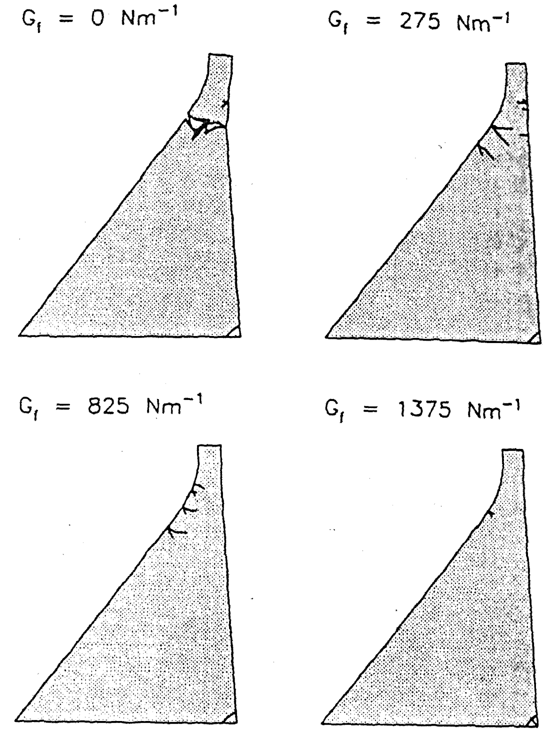

Figure 7: Crack pattern at 20 seconds for different fracture energy values

This fundamental difference of the behaviour of the reservoir has a direct consequence on the crack propagation dynamics. The quite different interaction forces on the dam upstream face influence the internal stress field of the dam. Thus, as shown in Figure 6, the crack pattern related to a compressible fluid differs from that obtained assuming an incompressible fluid.

3.2 Influence of concrete softening

The strain softening represents a further energy dissipation mechanism: Opening a crack requires a certain effort against the cohesive forces caused by the residual tensile stresses.

If no strain softening would be present, the loading capacity of portions of the structure would disappear at crack formation. The presence of strain softening, however, reduces this impact onto the neighborhood of the growing crack. What may be expected is a reduction of the crack formation according to the amount of energy needed to form crack surfaces.

In Figure 7 the crack pattern resulting from different values of fracture energy are shown. The analysis has been performed without taking into account the aggregate-interlock mechanism. These results are produced with an earthquake peak ground acceleration of 1.7 ms^{-2}.

For values of fracture energy in the range of $G_f = 150 - 300$ Nm^{-1} , measured on mass concrete specimens (Brühwiler 1989), the results suggest that there is little influence on the crack formation.

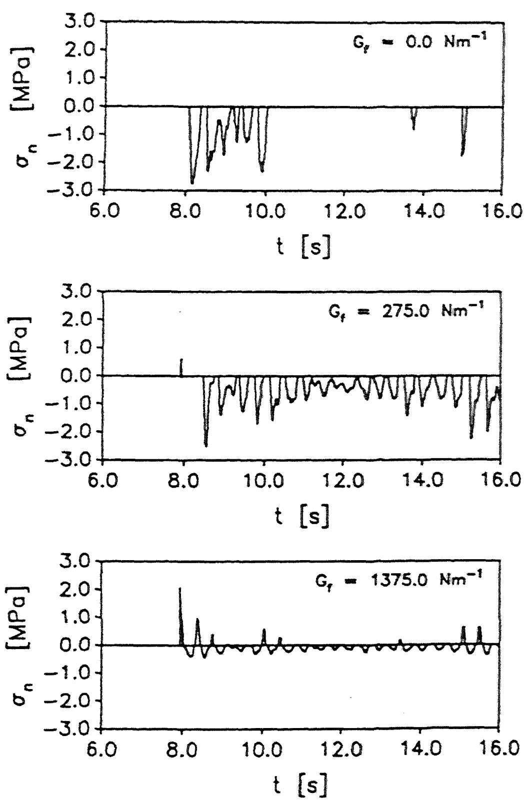

Figure 8: Average normal stresses across a crack for different fracture energy values

The results lead to the following conclusions:

- A fracture energy value in the range found for mass concrete seems to have little influence on the number of cracks produced compared to the case with vanishing fracture energy. However, if the aggregate-interlock mechanism is absent, the crack pattern may be influenced.

- In order to produce a relevant reduction of the number of cracks, the value of the fracture energy has to be increased to unrealistic values ($G_f = 825, 1375$ Nm^{-1}).

The model yields results which are essentially compatible with the experimentally well established physical phenomena that more ductile materials are less sensitive to crack propagation.

For a fixed tensile strength f_{ct} the fictitious crack model allows a variation of the fracture energy by an adjustment of the maximum effective crack-width w_{max} (see Figure 2). A larger maximum effective crack-width gives a bigger fracture energy. As a consequence, the residual tensile strength decreases less rapidly with the crack width. Thus the section does not loose its load carrying capacity abruptly as it would be the case for vanishing fracture energy. This effect can be seen in Figure 8, where the average normal stresses for the second crack element of the dam top is shown. Whereas for vanishing fracture energy only compression forces are transferred through the crack, a fracture energy value of 275 Nm^{-1} produces a small peak of tensile forces shortly after the crack formation. Afterwards only compression forces are transferred through the crack.

A quite different behaviour is exhibited at a fracture energy of 1375 Nm^{-1}. As shown in Figure 8, the strain-softening is effective over a long time period after crack formation. The load carrying capacity of the section will be eventually reduced but the energy requirement is larger. This effect is quite beneficial and reduces the number of cracks.

3.3 Influence of aggregate-interlock

Test results on mass concrete show that a crack may propagate completely inside the matrix or along the matrix-aggregate interface. As a consequence, very rough crack surfaces result in mass concrete due to the very large aggregate size used (the maximum aggregate diameter may reach 120 mm). For crack-opening widths less than the maximum roughness a part of the aggregates interlock so that a displacement of the crack surfaces relative to each other is only possible under the action of substantial shear forces.

Reliable test results for mass concrete determin-

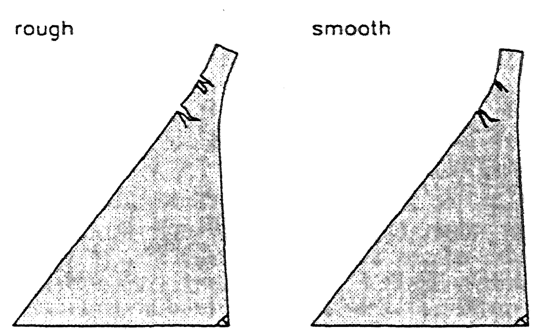

Figure 9: Crack pattern at 20 seconds for rough and smooth crack surfaces

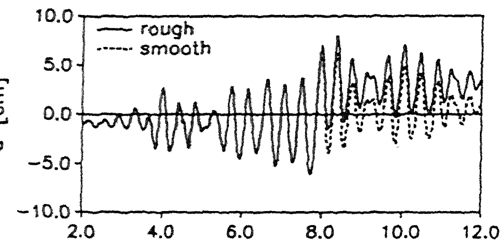

Figure 10: Horizontal displacement at the dam crest u for rough and smooth crack surfaces

ing the relationship between the relative slip and the shear forces acting across the crack are not available up to day. Analogous results for plain concrete have been presented by several authors. Laible, White and Gergely (1974) give the best information for our purpose. In absence of specific information, we assume that mass concrete behaves qualitatively like plain concrete.

Shear and normal forces acting on the crack surfaces and their roughness itself may affect the crack formation. They change the stress field in the neighbourhood of the crack. This may increase or reduce the crack formation according to the resulting tensile stresses ahead of the crack tip.

Modelling the roughness allows the transfer of compression forces even when the crack is not fully closed: A small relative displacement of the crack surfaces at open crack condition leads for closing cracks to a premature transfer of compression forces compared to smooth surfaces. Furthermore it will be very unlikely that all cracks close perfectly after the earthquake ground motion has vanished. So some cracks will remain partially open leading to an unrestorable deformation of a portion of the dam.

These effects are shown in Figure 9. A comparison of the crack pattern (on the left with aggregate interlock (rough) and on the right without aggregate-interlock (smooth)) shows a slight increase of the number of cracks when the aggregate-interlock mechanism is active. The transfer of forces across the crack tends to increase the tensile stresses in front of the crack tip facilitating the crack growth. This behaviour suggests, that the aggregate-interlock mechanism has the tendency to reduce the loading capacity of the section.

Including the aggregate-interlock mechanism, some cracks remained open whereas for smooth crack surfaces they closed neatly. This effect is shown in Figure 9, where for rough erack surfaces the upper part of the dam remained inclined towards the reservoir. The different time evolution of the horizontal displacement at the dam crest is represented in Figure 10.

4 CONCLUSIONS

The influences of the fluid compressibility, of the strain-softening and of the aggregate-interlock on the crack formation in concrete gravity dams subjected to earthquake loading has been studied. The compressibility of the fluid and the aggregate-interlock mechanism have significant effects on cracking and should be taken into account in nonlinear analysis of dams.

The strain-softening mechanism has been found to be of minor importance. A comparison with results produced with vanishing fracture energy shows that the fracture energy of mass concrete is too small to reduce significantly the crack formation. This suggests that brittle crack propagation occurs in concrete gravity dams.

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