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EFFECTS OF CONTRACTION JOINT MOVEMENTS AND CONCRETE NONLINEARITY ON THE SEISMIC RESPONSE OF ARCH DAMS

A. G. Razaqpur D. T. Lau B. Noruziaan

Department of Civil and Environmental Engineering
Carleton University, Ottawa, Canada K1S 5B6

ABSTRACT

During an earthquake, adjacent monoliths separated by contraction joint in an arch dam may undergo relative movement, causing the joint to open and/or slip. The alternating compressive and tensile dyanmic forces resulting from the joint movement may lead to failure of the concrete in the adjacent monoliths. Tensile cracks can occur in the dam body as a result of the redistribution of the arch stress in the cantilever direction. Furthermore, partial opening at the joint may cause overstress in the concrete in the compression zone of the joint. Previous nonlinear dyanmic analysis of arch dams have been confined to the nonlinearity arising from the joint movements. In the present study, the combined nonlinearity effects from the opening and closing of contraction joints and from the tensile cracking and compressive failure of concrete are investigated. In the study, a bounding surface model and a smeared crack approach are adopted to model the nonlinear material behaviour of concrete. The proposed nonlinear analusis models are implemented in a finite element program. Numerical results on the dynamic behaviour of a typical arch dam are presented in a case study, including the displacement and stress time history responses, and the extent of the damaged concrete material.

KEYWORDS

Arch dams; concrete; cracks; earthquake; finite elements; joints; modelling; nonlinear material.

INTRODUCTION

Due to their large size, arch dams are built as a series of monoliths, separated by contraction joint. Under static loads, due to the hydrostatic pressure behind the dam, the joints are under compression, and the compressive forces are transmitted along the arch axis to the dam abutments. During an earthquake the adjacent monoliths may undergo relative movement, causing the joints to open and/or slip and the dynamic forces may impose alternating compressive and tensile forces on the joints. If the tensile forces become larger than the static compressive forces acting on the joint, the joint will open up and it will release a significant amount of its tensile forces in the arch direction, making the structure more flexible and possibly over stressing the monoliths in the cantilever direction. Furthermore, the compression zones on the joint face may be over-stressed due to partial opening and the attendant reduction in the load bearing area of the joint.

In the past many studies have been carried out to investigate the static and dynamic elastic response of arch dams. Nonlinear dynamic analyses have been confined to the nonlinearity arising from the joint movements (e.g. Niwa and Clough, 1982, Row and Schricker, 1984, Dowling and Itall, 1989, Taskor and Jurukovski, 1988, Honberg, 1991, Fenves *et al.*, 1989, Bolognini *et al.*, 1992, Noruziaan *et al.*, 1995). There have been few, if any, studies about the effect of compressive over-stress or tensile crackers, and the ensuring damage, on the seismic response of arch dams. The objective of the present investigation is to study the combined effects of concrete nonlinearity and joint movement on the seismic response of arch dams.

CONCRETE CONSTITUTIVE MODEL

Several constitutive models are available for concrete subjected to cyclic loading. Due to its clarity and relatively good performances, the bounding surface model is adopted in the present study. The details of this model may be found in Paagnmi *et al.* (1992) and Nouroozian (1995).

Briefly, the bounding surface is a surface in stress space enclosing the current stress joint. For any stress point, there is an image point on the surface which is determined by a mapping rule. The bounding surface may expand or shrink to model the hardening or softening behaviour. The plastic modulus, which relates the stress increments to plastic strain increments, is assumed to be a function of the distance between the stress point and its image. Plastic deformation can occur at any stress state within the surface. If an elastic nucleus is defined inside the bounding surface, the stress within this elastic surface corresponds to purely elastic strains. Increments of strain $d\epsilon_{ij}$ are related to increments of stress $d\sigma_{kl}$ as

$$d\epsilon_{ij} = C_{ijkl} d\sigma_{kl} \tag{1}$$

where the compliance tensor C_{ijkl} is defined as

$$C_{ijkl} = \frac{1}{H^e}\delta_{ik}\delta_{jl} + \frac{1}{3H^p}\frac{1}{\tau_o}\left(\frac{S_{ij}}{\tau_o} + \frac{\delta_{ij}}{3}\rho\right)S_{kl} + \left(\frac{1}{9K_t} - \frac{1}{3H^e}\right)\delta_{ij}\delta_{kl} \tag{2}$$

Note that due to the coupling between that deviations stresses and the volumetric strain, C_{ijkl} is not symmetric. In the above, the plastic modulus H^p, the generalized shear modulus H^e, the bulk modulus K_t, and the shear-compaction dilatancy ρ, are the parameter of the bounding surface model.

When applying (2) in the current study, it was discovered that in the strain softening region, the rigidity matrix of concrete would become unreasonably large, leading to numerical difficulties. Consequently, it was decided to make the rigidity matrix null once the stress point touched the bounding surface.

For modelling the tensile(cracking) behaviour of concrete, the smeared crack approach was adopted. For each sampling point the principle stresses and their directions are evaluated. If the principal tensile stress is found to exceed the tensile strength of concrete, a crack is assumed to have formed in a plane normal to that tensile stress. Subsequent cracks are assumed to form orthogonal to the first crack. The tensile strength of concrete subjected to triaxial stresses is determined using

$$\sigma_{tu}^{(i)} = f_t'\left(1 + \frac{\sigma_j}{f_c'}\right)\left(1 + \frac{\sigma_k}{f_c'}\right) \tag{3}$$

$$\sigma_{tu}^{(i)} \leq f_t'$$

where $\sigma_{tu}^{(i)}$ is the tensile strength of concrete in principal direction i, f_t' and f_c' are the uniaxial tensile and compressive strength of concrete, respectively, and σ_j and σ_k are the concomitant principal stresses orthogonal to direction i. In (3) compression is assumed to be negative.

The proceeding tensile model is simple, but due to the wide scatter in the experimental values of the tensile strength of concrete, the use of more sophisticated models may not be warranted in practice.

The algorithm for the complete tensile and compressive behaviour modelling is shown in Fig.1. Following this algorithm, the foregoing constitutive laws were implemented in a computer program called Bandaab2, which also accounts for the opening and closing of the contraction joints. This program is specifically developed for the nonlinear seismic analysis of concrete arch dams (Norouzian, 1995). The program is the result of extensive modifications of and extension to the computer program ADAP88, developed at the University of California at Berkeley (Fenves et al., 1989). Currently the material nonlinearities can be used only in the 3-D solid finite elements within the program.

The Morrow Point dam, a modern arch dam completed in 1968 in the United States (Thomas, 1976), is selected for this case study. Its hight is 143 m with a crest length of 226 m. The base thickness of the dam is 21.0 m and its crest thickness is 3.66 m. This dam has been the subject of a number of experimental and numerical studies (NRC, 1990). In these analyses, the modulus of elasticity of concrete is taken as 23.9 Gpa, its Poisson's ratio as 0.20 and its mass density is 2070 kg/m^3. The tensile strength of concrete is assumed to be $0.15f'_c$. The foundation is assumed to be rigid. The water effect is taken into account. The water is assumed to be incompressible. The hydrodynamic effect is modelled by the diagonalized added mass concept used by Fenves *et al.* (1989). Fig. 2 shows the finite element mesh for half of the dam with line DE being the axis of symmetry.

The dam is subjected to the stream and the vertical components of a typical recorded ground motion. The time histories of the applied ground motions are presented in Figs. 3(a) and 3(b). The pseudo-acceleration response spectra for these two earthquake records, assuming a damping ratio of 5% of critical damping, are plotted in Fig. 4. The periods of the first symmetric vibration mode of the dam for the full and empty reservoir cases are also shown in this figure.

The time history responses of the arch dam were determined for the duration of the strong ground shaking of the applied earthquake record (10 seconds). In these analyses, the reserviour was assumed to be full which would produce the maximum inertial effect of the reserviour liquid loading. The values of Rayleigh's proportionality constants were chosen such as to provide a 5% modal damping in the first and fifth vibration modes of the monolithic empty reservoir model. The values of Newmark's time integration constants, i.e. β and γ , were assumed to be 0.36 and 0.7 and the time step interval was taken to be 0.005 seconds.

Although a large number of response time histories were obtained, only a few are presented here. However, the conclusion drawn from the results presented here are equally applicable to other response histories. The responses at the locations A, B, C, D, E and F of the dam, as shown in Fig.2, are studied.

In order to investigate the propagation of damage within the dam, the damaged elements of the dam based on the implemented models have been identified. In the present contest, the term "damage" does not refer to the theory of damage mechanics, but when an integration point within a finite element experiences cracking or compressive failure during the response, the element is identified as damaged. The damaged zones after 8 second of the ground motion are shown in Fig. 5. Although Fig. 5 identifies damage in a generic sense, closer examination of the results revealed that most of the damage is due to cracking rather than compressive over-stress. However, cracking generally occurred in zones subjected to combined tension-compression.

Since (3) indicates that the tensile strength of concrete in a given direction is diminished by concomitant compression in the orthogonal direction, the effect of high compressive stresses on damage cannot be ignored. This observation leads to the conclusion that models which do not correctly model compressive behaviour may not be able to accurately predict the formation of cracks and their impact on the nonlinear seismic response of arch dams.

Although not shown here, the analysis revealed that initial damage occurred at the heel of the dam on the upstream face after 4 seconds of ground acceleration. But later most of the damage occurred at the upper level of the dam on the downstream face. Since hydrodynamic pressure at the upper level is small, the damage in the latter zones may not pose serious safety problems.

Figs. 6(a) and (b) show the typical stress time histories for a point within the body of the dam. The results show that there is a significant change in the response at the time 7 second after the commencement of the ground motion, which corresponds to the time of the peak ground excitation.

Fig. 7 shows the effect of concrete nonlinearity on the displacement response at point D of the dam. The results show that tensile cracking tends to increase the maximum response in the dam. However, the time histories of the displacements of the dam do not show very significant difference between the results of the linear and nonlinear analyses. This may be due to the scattered and relatively small amount of damage within the overall body of the dam. Fortunately, the scattered nature of the damage may present coalescence of the damaged zones and that will minimize local failure.

CONCLUSIONS

Although the present study was restricted to a particular dam geometry and to a specific ground motion, nevertheless it was determined that concrete arch dams could crack during a strong earthquake. Although cracking was detected on both the upstream and downstream faces of the dam, most cracks formed on the downstream face which is not as critical. It was shown in the present study that proper modelling of the nonlinear response of concrete arch dams requires that both the compressive and tensile behaviour of the concrete be properly modelled. In the case of the particular dam that was analysed, failure due to compressive over-stress was not detected, but high compressive stresses did lead to reduction of tensile strength in the principal tensile stress direction which in in turn caused cracking. Finally, despite the formation of cracks in some parts of the dam, the effects of cracking and other nonlinearities on the response of the dam were found to be small.

ACKNOWLEDGEMENT

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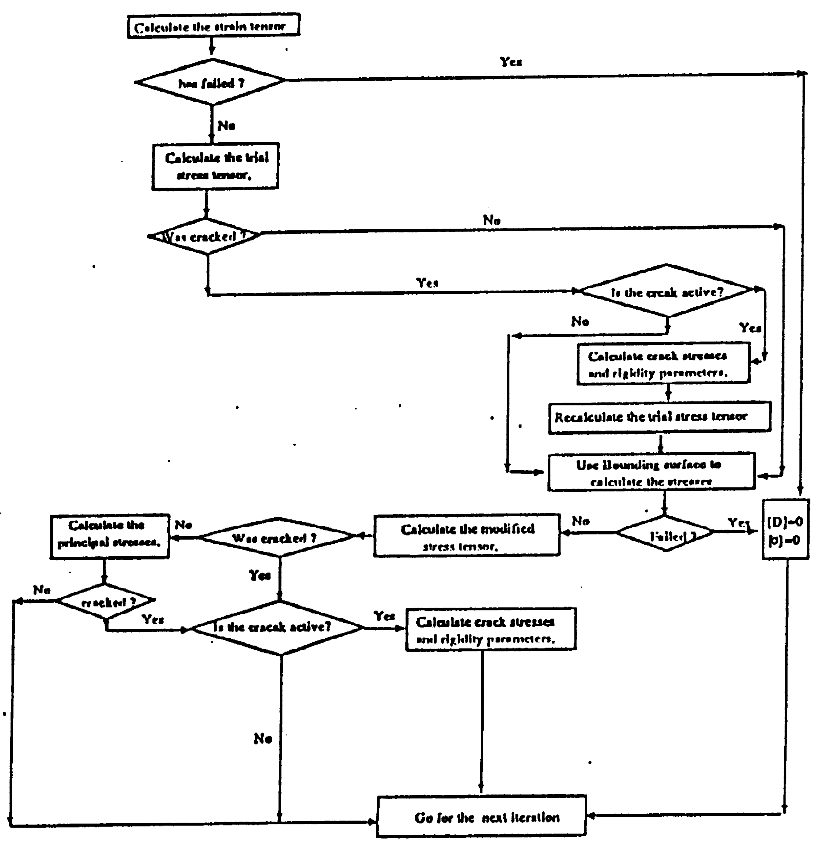


Fig. 1. Algorithm for the combine tensile and compressive model of concrete

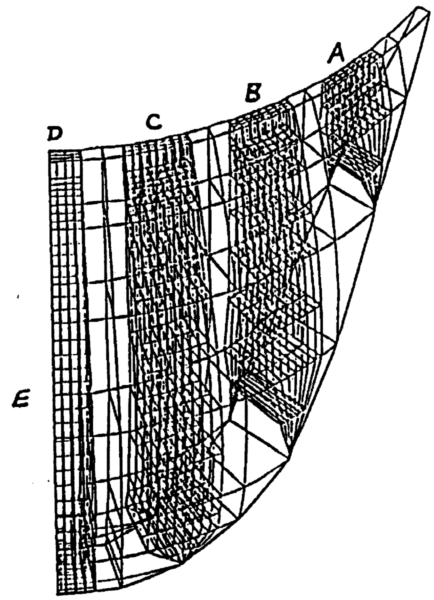


Fig. 2. The finite element mesh

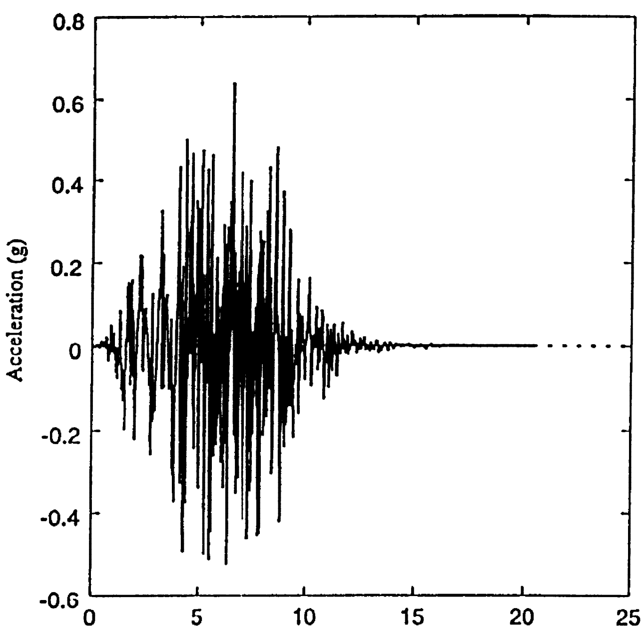


Fig. 3 (a). Accelerograph for the stream component of the applied earthquake

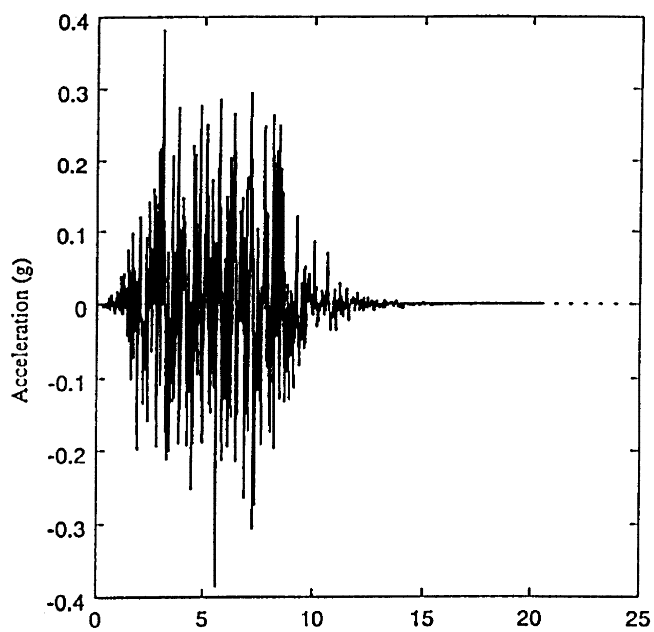


Fig. 3 (b). Accelerograph for the vertical component of the applied earthquake

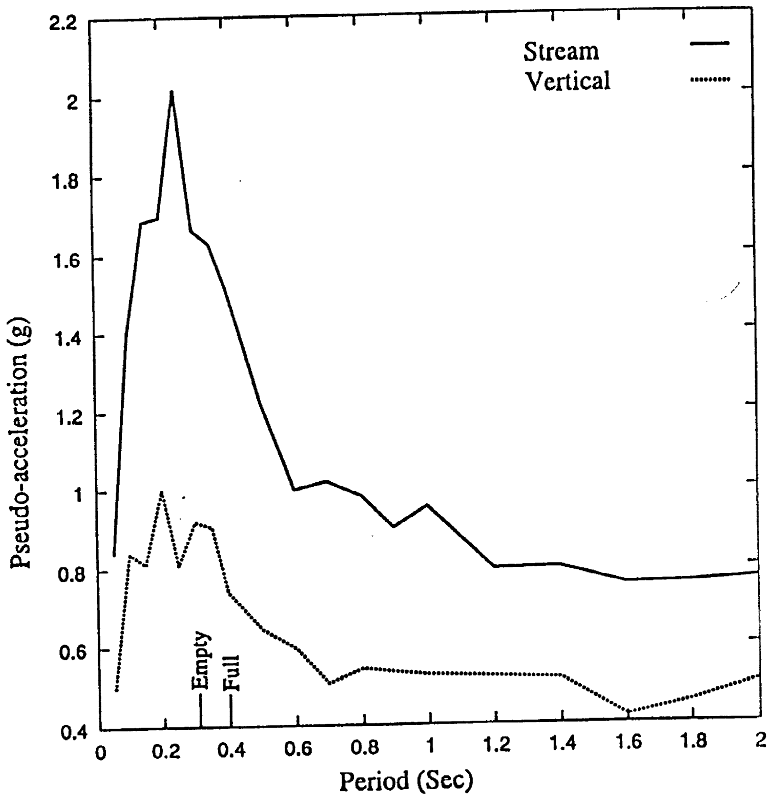


Fig. 4. Pseudo-acceleration Response Spectra for Earthquake Ground Motion (5% critical damping)

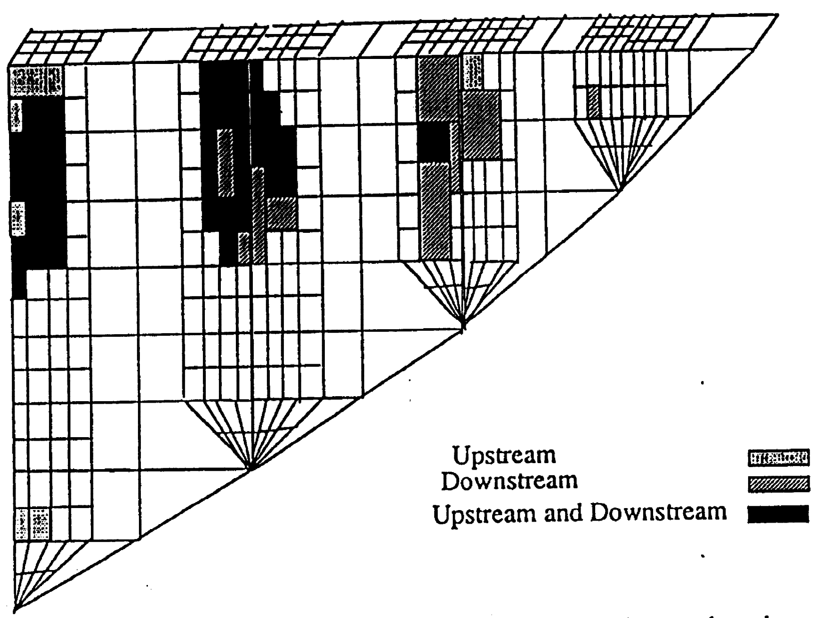
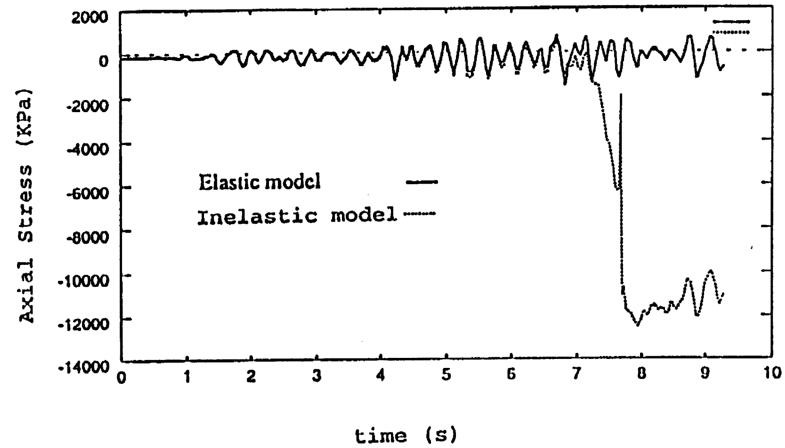


Fig. 5. Damaged elements after 8 seconds of the applied ground motion for the new mesh (based on the combined model)



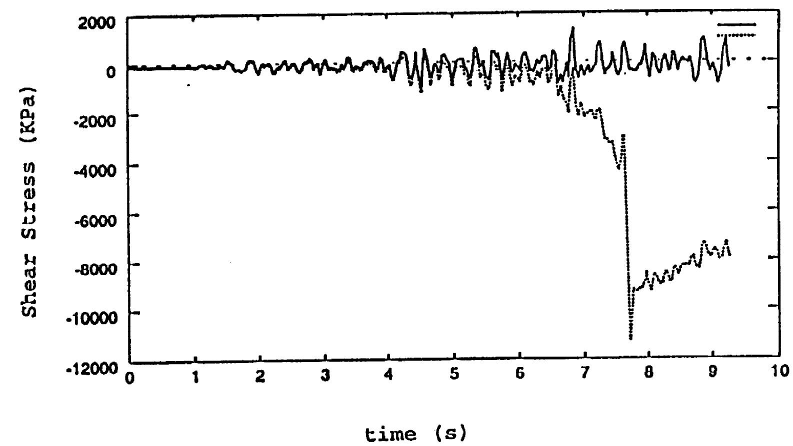


Fig. 6. Stress time history

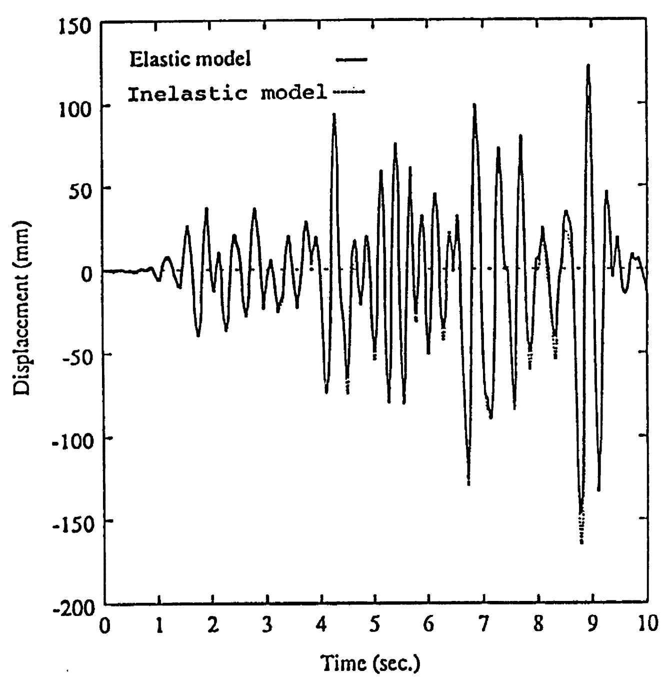


Fig. 7. Stream component of the displacement on the upstream face at point D