Effect of Contraction Joint Movements on the Seismic Response of Concrete Arch Dams

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ABSTRACT

Concrete arch dams are built of monoliths, separated by contraction joints, in order to release some of the stresses in the arch direction of the dam due to thermal effect, shrinkage and loads. During strong seismic excitations, the two faces of a contraction joint may move relative to each other. The movement can be in the normal (opening) or tangential (slip) direction of the joint or both. In this paper effects of joint movements on the seismic behaviour of a typical arch dam is studied. The dam is modelled by the finite element method taking into account the hydrodynamic effect of the reservoir and the flexibility of the foundation. An appropriate joint element capable to simulate the opening and slip behaviour, and the shear key effects of the contraction joints has been developed. Results of numerical analyses have shown that tangential slippage may lead to a considerable amount of residual displacements and stresses in the dam, which can have significant effects on the seismic and post-earthquake behaviour of arch dams.

INTRODUCTION

Concrete is a brittle material and is susceptible to cracking due to its low tensile strength. To avoid this and other crack problems due to shrinkage and temperature drop in mass concrete, arch dams are built as assemblages of monoliths separated by contraction joints. Also, it is common in arch dams to have shear boxes or shear keys for the transfer of shear forces across the joints, especially in dams built in seismic active regions, or if there is a possibility of foundation breakdown so that the transfer of shear stresses between the dam monoliths by friction can not be relied upon.

During an earthquake, adjacent monoliths in an arch dam, that are separated by a contraction joint, may move relative to each other, resulting in the opening and closing of the joint and possible shear movements at the joint surfaces. If the dynamic tensile load in the arch direction is more than the static compressive force, the contraction joints will open up and release a significant amount of the tensile forces in the arch direction, making the structure more flexible in this direction with the result of possible over-stress in the monoliths either in tension or compression in the cantilever direction. On the other hand, it is also possible that the compressive face of the joint can be over-stressed due to partial opening of the joint and the resulting reduction of the load bearing area at the joint. Several Researchers have studied the effect of opening-closing of contraction joints in arch dams (Niwa and Clough 1982, Row and Schricker 1984, Dowling and Hall 1989, Weber et al 1990, Fenves et al 1992). However, in these previous studies,the possibility

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of shear slippage of the joints has not been considered.

Based on results obtained from scale model tests and numerical studies, Taskov and Jurukovski (1988) concluded that sliding of the contact area, crushing of the contact zone, opening of joints, and reduction in friction over the contact area, all have significant effects on the seismic response of arch dams.

In another study, Hohberg (1991) implemented a rather detailed model for the joints which considered frictional slippage and slippage due to separation. Asperity of the joint surface was also modelled. But the hydrodynamic effects were not included. Shear keys were modelled by increasing the height of the asperities.

The above literature survey reveals that there is a need for a better understanding on the effects of joints on the behaviour and performance of arch dams. To fill this gap, a joint model that can simulate both opening-closing and slippage non-linearities, as well as the shear keys effects has been developed and implemented in the arch dam computer program ADAP88. The hydrodynamic loading effect of reservoir on the joint behaviour has been considered.

JOINT ELEMENT

In this study the contraction joints are modelled by zero-thickness joint elements. The element consists of two adjacent surfaces which are completely coincident with each other during the initial at rest condition. The kinematics of the element are expressed in terms of the relative displacements of the two faces of the joint, $U = U^{top} - U^{bot}$. The relative normal and tangential displacements between the surfaces of the joint produce internal resistant forces or stresses. The relationship between these relative displacements and the surface tractions are expressed using an element constitutive law. In the elastic state of behaviour, this relationship is written as follows

$$\left\{ \begin{array}{c} \sigma \\ \tau_1 \\ \tau_2 \end{array} \right\} = \begin{pmatrix} k_n & 0 & 0 \\ 0 & k_s & 0 \\ 0 & 0 & k_s \end{pmatrix} \left\{ \begin{array}{c} v \\ u_1 \\ u_2 \end{array} \right\}$$

where σ is the normal stress and is assumed to be positive in tension, and τ_1 and τ_2 are the two components of the shear stress acting on the contact surface in two perpendicular directions, k_n and k_s are the penalty parameters for the normal and inplane directions respsectively.

The following basic assumptions are considered in the derivation of the constitutive model for the proposed joint element: (1) The joint has negligible tensile strength. (2) The joint tangential stiffness will be reduced substantially (theoretically to zero) when the joint opening exceeds a pre-defined slip margin δ. (3) The normal stress and normal stiffness in an open joint are reduced to zero. (4) The joint behaves elastically in sliding when the joint is open, provided the shear stress is less than the shear strength or apparent cohesion of the joint. (5) During the open state, when the shear stress exceeds the shear strength limit of the joint, the sliding of the joint is resisted by a constant shear force resulting from its apparent cohesion. (6) There is no coupling between the normal and shear displacements when the joint is open. The normal stress remains zero. (7) When the joint is closed, the friction between the two faces of the joint becomes effective in resisting the sliding motion. The joint behaves elastically or elasto-plastically, with coupling between shear and normal displacements. (8) In the plane of the joint, the behaviour is assumed to be isotropic. (9) The plasticity model for sliding is assumed to be of the Mohr-Coulomb type, which is a reasonable assumption for joint slippage (NRC 1990).

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The behaviour of a joint is divided into two basic states: the open state and the closed state. For a joint in open state, that is when the normal relative displacement v is positive, a threshold slip margin δ is defined to simulate the effects of the shear keys. Whenever the slip margin is exceeded, the tangential penalty is reduced. The slip margin and the amount of the penalty reduction depend on whether the joint is keyed or un-keyed, and whether the key is beveled or not.

The normal stiffness of the joint is reduced to zero when it is open and no stress is transferred between the two faces. As soon as the joint is closed with $v \leq 0.0$, the stiffness of the joint recovers.

The sliding behaviour is elastic when the shear stress is less than the limiting value c. For un-keyed joints, this c value is the assumed apparent cohesion, and is much smaller than that of a keyed joint. For a keyed joint, c represents the shear or bearing strength of the keys. Exceeding this limit, the joint slides with constant shear resistance and the unloading is fully elastic. Depending on the magnitude of v in comparison with the slip margin δ, the magnitude of the tangential penalty k_s changes from a maximum value when $v \leq \delta$, to a much smaller value (theoretically zero) when v exceeds the limit δ in the fully open state.

The joint slippage in the closed state is resisted by friction. The two parameters which govern this behaviour are the friction angle and the apparent cohesion. In the present study, a three dimensional model based on the two dimensional Mohr-Coulomb yield-failure criterion is developed to simulate the joint slippage behaviour in the closed state. A similar version of this model with a different implementation can be found in the reference (Hohberg 1992).

In the present formulation, the loading function in the contact stress space can be written as follows

$$f = \tau + \mu\sigma - c$$

where

$$\tau = \sqrt{\tau_1^2 + \tau_2^2}$$

and

$$\mu = tan\phi$$

In the above equations, ϕ is the friction angle and c is the apparent cohesion of the joint.

NUMERICAL EXAMPLES

The analysis results of Morrow Point Dam subjected to ground motions in the upstream-downstream direction are presented. The finite element mesh of the dam with seven contraction joints is shown in Fig.1. Due to symmetry of the problem only half of the dam is modelled. The time history for the applied ground motion is shown in Fig.2. Three different joint configurations are considered: (1) $\delta = 30$ cm, $c = \infty$ and $\phi = 90^o$ representing no free and no frictional slippage in the joint, (2) $\delta = 3.2$ mm, $c = \infty$ and $\phi = 90^o$ representing free slippage but no frictional slippage and very strong shear key; (3) $\delta = 30cm$, $c = 0.1f_c'$ and $\phi = 90^o$ representing no free slippage but a shear key with finite shear or bearing strength and no frictional slippage.

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Figs.3 to 18 show the relative displacements and tractions in the joint element at point B. For case 1, although the shear displacement on the joint surface is negligble, the joint still has large shear stresses as shown in Figs. 3 and 4. As can be noted in Figs. 7 and 9 for case 2, the joint slips at several instants, causing sudden jumps in the shear stress magnitudes. Fig. 11 in dicates that the joint opens more than the slip margin δ. Corresponding to these instants in Figs. 8 and 10 the shear stress drops to zero, showing no shear resistance. Effect of shear or bearing yielding of the shear key on shear slippage is not as significant as the effect of free slippage, as can be observed in Figs.13 to 18. The results of the three cases as given in Figs. 6, 12 and 18 show that the time history of the normal stress is affected by the joint configurations.

Figs. 19 and 20 show that free slippage of the joints after the slip margin has been exceeded causes larger displacements and stresses in the dam than those due to yielding of the shear keys. It is noted that shear slippage can cause some residual stresses in the dam, which can significantly affect the post-earthquake behaviour of the dam as can be observed in Figs. 21 and 23.

CONCLUSION

The effects of the joint opening-closing, free and shear slippage of contraction joits and the shear keys on the seismic response of a typical arch dam has been studied in this paper. The numerical results show that, the nonlinear shear slippage beahviour in contraction joints has significant effect on the response of the arch dams. Considerable residual displacements and stresses can remain in dams after the earthquake, which may affect the long term behaviour of theses structures.

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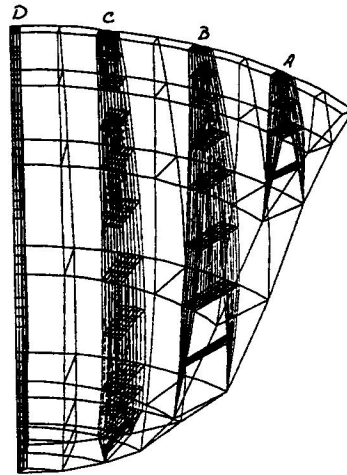
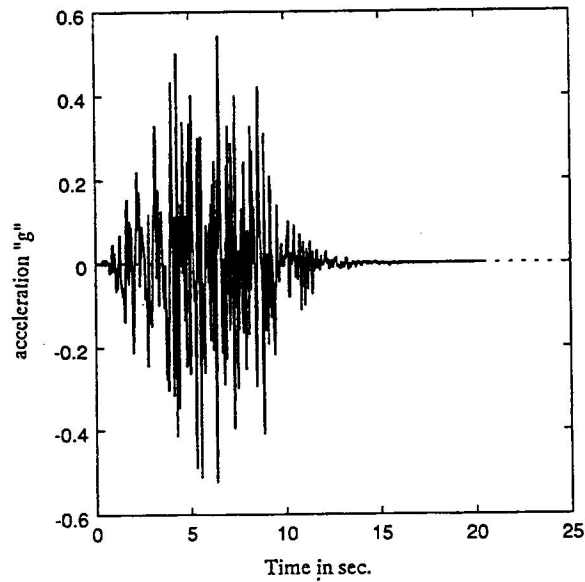Fig. 1. The finite element mesh and the sampling points.
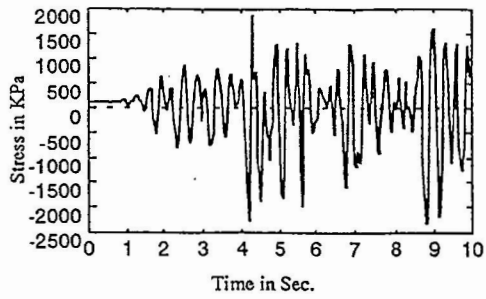

Fig. 2. Accelerograph of the applied earthquake

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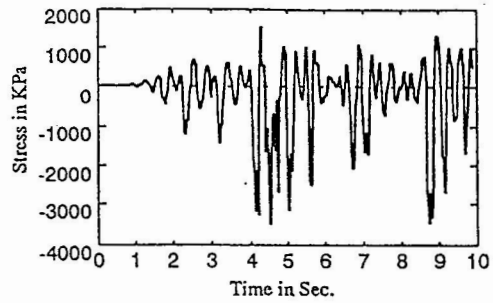Fig. 3. Joint vert. shear stress at pt. (B), case (1)
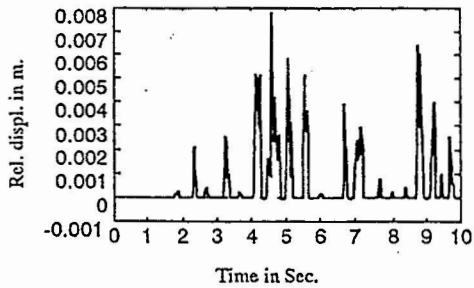

Fig. 4. Joint Horiz. shear stress at pt. (B), case (1)

Fig. 5. Joint normal displ. at pt. (B), case (1)
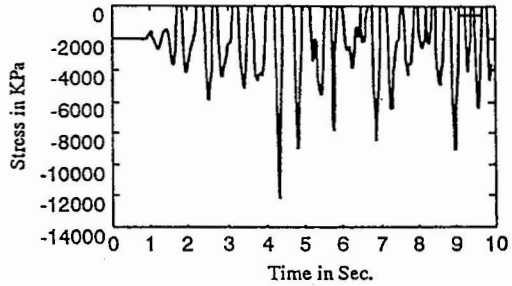
Fig. 6. Joint normal stress at pt. (B), case (1)
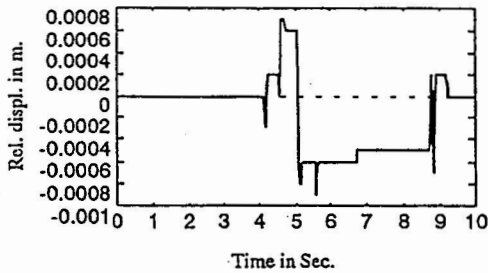

Fig. 7. Joint vert. shear displ. at pt. (B), case (2)
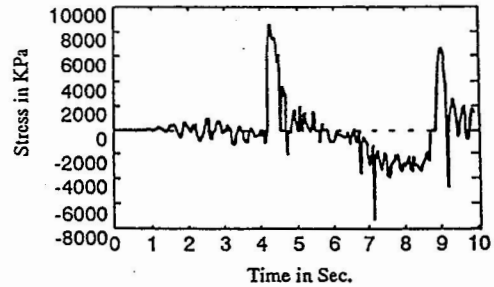

Fig. 8. Joint vert. shear stress at pt. (B), case (2)
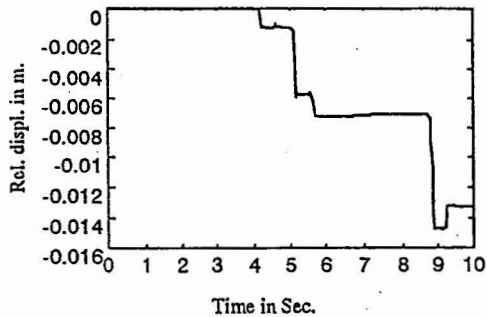
Fig. 9. Joint horiz. shear displ. at pt. (B), case (2)
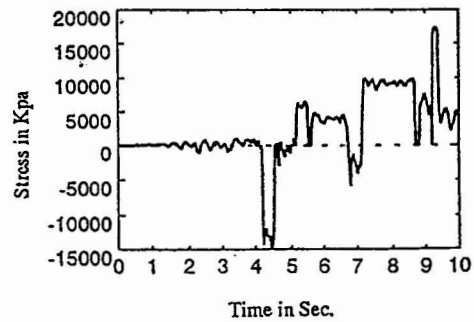
Fig. 10. Joint horiz. shear stress at pt. (B), case (2)

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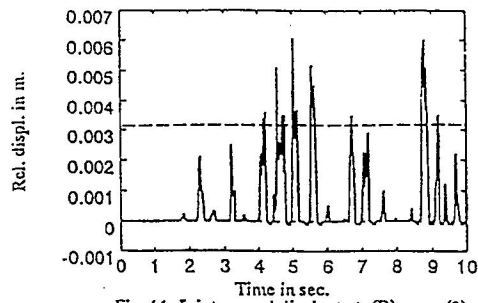
Fig. 11. Joint normal displ. at pt. (B), case (2)

Fig. 12. Joint normal stress at pt. (B), case (2)
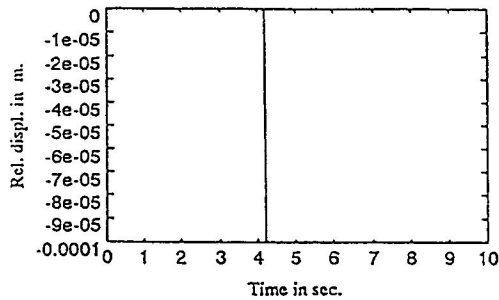
Fig. 13. Joint vert. shear displ. at pt. (B), case (3)

Fig. 14. Joint vert. shear stress at pt. (B), case (3)
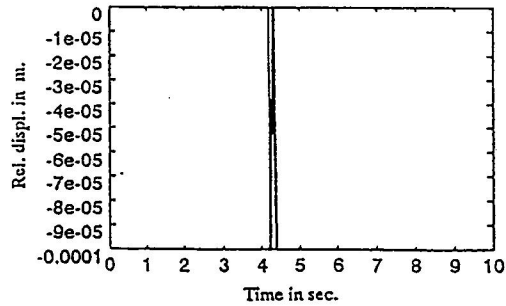
Fig. 15. Joint horiz. shear displ. at poit (B), case (3)

Fig. 16. Joint horiz. shear stress at pt. (B), case (3)
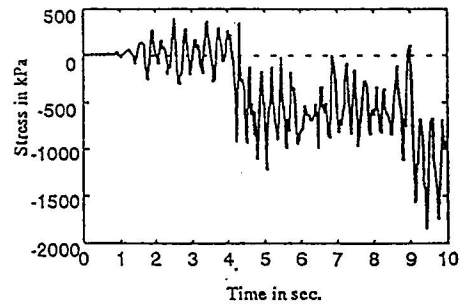
Fig. 17. Joint normal displ. at pt. (B), case (3)
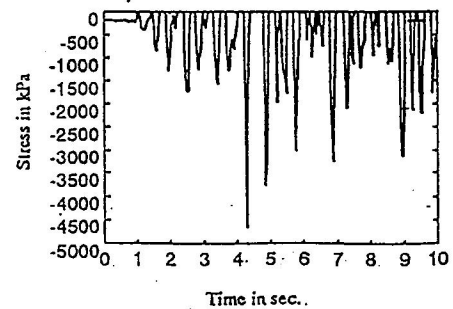
Fig. 18. Joint Normal stress at point (B), case (3)

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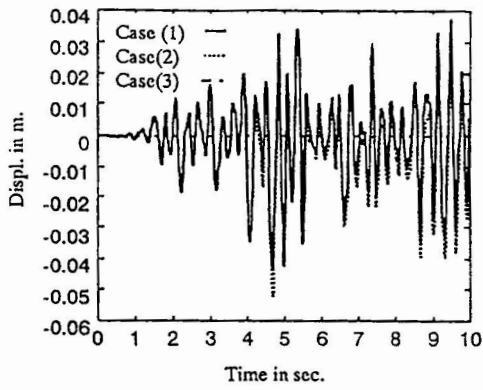
Fig. 19. Stream direction displ. at pt. (B)
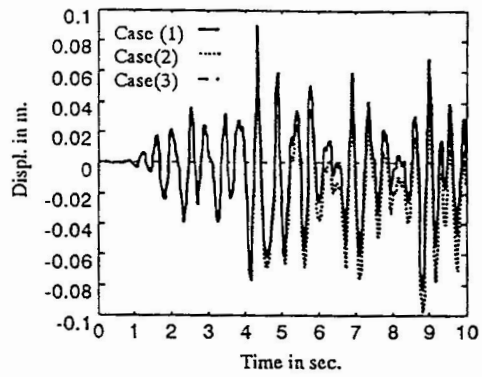
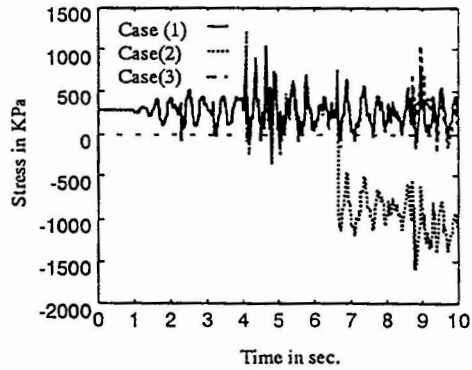Fig. 20. Stream direction displ. at pt. (C)

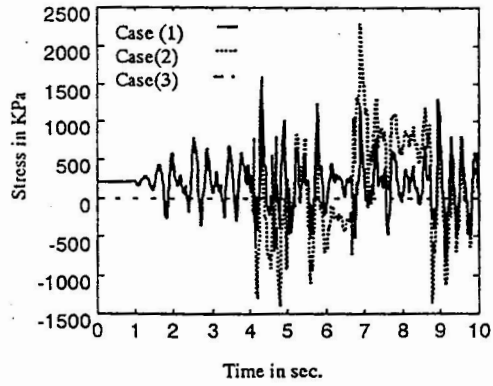Fig. 21. Cant. comp. of stress for 3 D elem. at pt. (A)

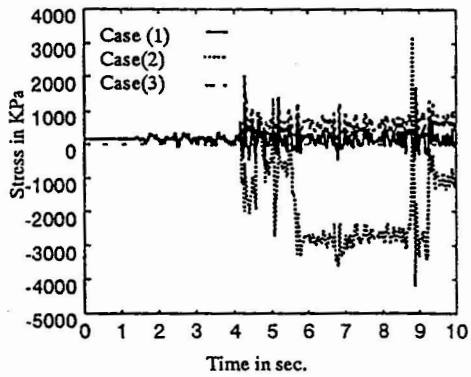Fig. 22. Cant.comp. of stress for 3 D elem. at pt. (B)
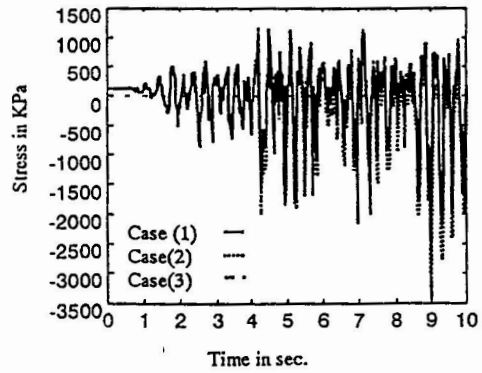

Fig. 23. Cant. comp. of stress for 3 D elem. at pt. (C)

Fig. 24. Cant. comp. of stress for 3 D elem. at pt. (D)

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