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Nonlinear earthquake analysis of arch dam/reservoir

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ABSTRACT: Concrete arch dams cannot develop significant tensile stresses in the arch direction during an earthquake because the contraction joints separating the cantilever monoliths will open. A dynamic analysis procedure using a nonlinear joint element simulates the joint opening behavior in the response of a typical arch dam to a maximum credible earthquake. The analysis shows that the maximum arch tensile stress of 2000 psi in a model with closed joints reduces to 800 psi when the joints open. The opening of the joints and release of arch action increases the cantilever tensile stresses to a maximum of 1200 psi at the downstream face compared with 1000 psi at the upstream face for the model with closed joints. It is necessary to include at least three contraction joints in the model of an arch dam to represent the effects of joint opening with reasonable accuracy.

1 INTRODUCTION

Concrete arch dams are usually constructed as cantilever monoliths separated by contraction joints. Since the joints cannot transfer substantial tensile stresses in the arch direction, the joints may open as the dam vibrates in response to earthquake ground motion. A seismic safety evaluation of an arch dam often relies on a linear dynamic analysis assuming the dam is a monolithic structure. The joint opening behavior is not represented, and hence a linear analysis can show unrealistically large tensile stresses in the arch direction.

The earthquake response of arch dams is further complicated by the important effects of dam–water interaction, dam–foundation rock interaction, and the spatial variation of the input motion along the interface between the dam and canyon. It is not possible to include these frequency–dependent effects along with the nonlinear joint behavior in an analysis procedure without some approximation.

A recently developed modeling technique and numerical procedure for computing the nonlinear earthquake response of arch dams provide improved understanding about the effects of joint opening (Fenves 1989). The joints are modeled with a nonlinear joint element, a detailed discretization near the joint provides resolution of stress concentrations, and the dam body is modeled with shell elements. A substructure procedure, in conjunction with the fact that only a few contraction joints in the dam have to be included in the model, provides an efficient numerical solution. The impounded water is represented as an incompressible fluid, the foundation rock is represented by a massless finite element model, and uniform free–field motion is specified along the canyon–dam interface.

This paper presents selected results from an extensive parameter study on joint opening behavior in the seismic response of an arch dam. The study specifically investigates Morrow Point dam, Colorado, U.S.A., subjected to a ground motion characteristic of a maximum credible earthquake at the site. The primary question examined in this paper is how the number of contraction joints included in the model of the dam affects the stress distribution.

2 SUMMARY OF ANALYSIS METHOD

The finite element model recognizes that contraction joints separate the cantilever monoliths, as shown in Figure 1. The cantilevers are modeled by sixteen–node three–dimensional shell elements near the abutments, and thick shell elements away from the abutments. The foundation rock is modeled by eight–node solid elements. As illustrated in Figure 2, several joint elements through the thickness of the dam model the opening and closing of a contraction joint.

The region of the dam adjacent to the contraction joints is modeled by three–dimensional solid elements to provide a transition with the shell elements and improve the resolution of the stresses near the joint elements. The number of solid elements through the thickness of the arch is equal to the number of joint elements through the thickness (Figure 2). The nodal points along the interface of the shell elements and the solid elements are kinematically constrained to remain in a plane.

The regions of the model between the contraction joints are substructures. The static and dynamic behavior of the cantilevers is assumed to be linear, so cracking of concrete in the substructures is not represented.

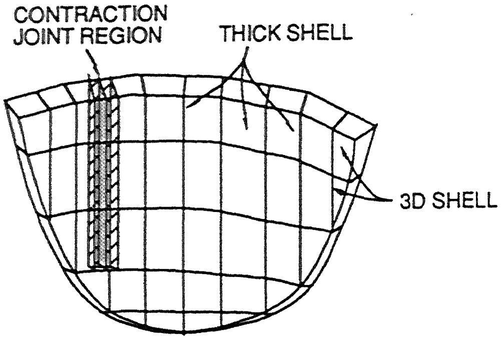


Figure 1. Finite element model of arch dam including contraction joint.

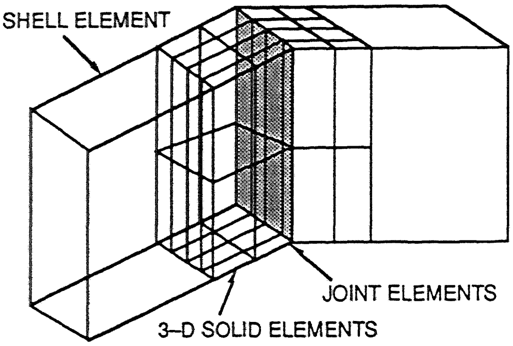


Figure 2. Detail of finite element model for contraction joint region.

The assumption of linear substructures leads to an efficient numerical solution procedure even with the nonlinear joint elements.

2.1 *Nonlinear joint element*

The nonlinear joint element represents the opening and closing of the contraction joints. It is similar to joint elements described by Hohberg (1988). The element develops resisting forces due to relative normal and tangential displacements between two coincident surfaces, as shown in Figure 3(a). The stress–displacement relationship for the element is shown in Figure 3(b). The stresses, q_i, in the joint are a nonlinear function of the relative displacements, v_i. Since the local coordinate system is orthogonal, the assumption is made that displacement in one direction only produces stress in that direction. The joint has a specified tensile strength, q_{0i}, in each direction. Once the strength is reached, the joint unloads and the subsequent tensile strength is zero. In the current study, the tangential displacements are constrained, although this can be relaxed to represent slippage when the joint is open.

The integrals for element tangent stiffness matrix and the restoring force vector are evaluated using Gauss quadrature. For a closed joint, 2x2 Gauss integration exactly evaluates the integrals. In the case of an open joint, 2x2 Gauss integration also produces sufficiently accurate results. The normal to the element surface at the origin is used as an approximation of the normal throughout the element.

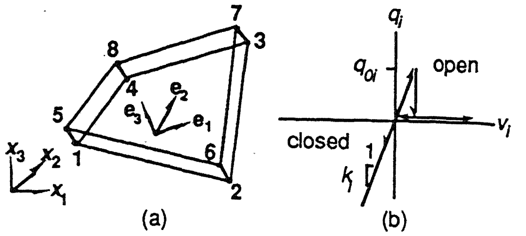


Figure 3. Nonlinear joint element; (a) geometry of element; (b) stress–relative displacement relationship.

2.2 *Substructure analysis procedure*

The equations of motion for a structure with a small number of nonlinear elements may be solved efficiently using a substructure procedure (Clough 1979). Arch dams are an example of such a structure because the cantilevers are assumed to be linear and a small number of joints are nonlinear. In the model of an arch dam, cantilever sections (as defined by the contraction joints in the model) and the foundation rock region are linear substructures, and the set of joint elements is a nonlinear substructure.

The substructure procedure used for the analysis of arch dams (Fenves 1989) is similar to earlier work (Row 1984). The equations of motion for the substructures are coupled by equilibrium and compatibility conditions at the boundaries. The constant–average acceleration method is used for time integration of the equations of motion, and a Newton–Raphson iteration achieves equilibrium in each time step. The substructure solution has several advantages compared with allowing nonlinear behavior in the entire system:

1. An equilibrium iteration during a time step only involves the degrees–of–freedom in the nonlinear substructure, resulting in a substantial reduction of computation for structures with a small number of nonlinear elements.
2. The stiffness matrix for the substructure is computed once because the states of the linear substructures do not change. Only the joint elements are linearized during an iteration.
3. The restoring force for a linear substructure is expressed in terms of the response at the boundaries of the substructure. This also results in a substantial reduction of computation when the number of boundary DOF in a substructure is small compared with the number of interior DOF.

Three static analyses of a dam represent the construction and loading sequence. In the first analysis gravity is applied to alternate cantilevers acting independently. The remaining cantilevers are loaded by gravity in the second analysis. The third static analysis, for the hydrostatic loads and temperature, uses the complete dam–foundation rock model with joint opening allowed.

2.3 *Dam–Water and Dam–Foundation Interaction*

Water compressibility affects arch dam response (Fok 1987) but the analysis including compressibility requires a frequency domain solution which precludes the nonlinear effect of joint opening. If water compressibility is neglected, dam–water interaction is represented by a frequency–independent added mass matrix and a time domain solution can be used. The added mass matrix can be computed from a finite element model of the impounded water (Kuo 1982).

The added mass matrix is full, however, and it couples all the wet nodes at the upstream face of the dam. This negates a major advantage of the substructure procedure because all substructures are mutually coupled through the impounded water. Since the principal goal of this study is to determine the effects of joint opening on the earthquake response of arch dams, dam–water interaction is simplified by diagonalizing the added mass matrix. The diagonal terms of the added mass matrix are scaled such that the total hydrodynamic force due to rigid body acceleration in each direction is the correct value for the incompressible water in the reservoir.

The modeling of the foundation region is complicated by the three–dimensional geometry of canyons and highly variable properties of the foundation rock. The common practice is to model a foundation region of dimensions approximately equal to the size of the dam. The mass of the foundation rock, and hence wave propagation, is neglected.

The finite element model of the foundation rock region is a massless, linear substructure with uniform support acceleration specified at the far boundaries. The stiffness matrix for the foundation region is statically condensed to the degrees–of–freedom at the dam–foundation rock interface. This matrix could be used in the analysis, but all the interface nodes would have to be included in the boundary partition for the substructure analysis. Numerical studies have shown that it is only necessary to retain the coupling between two adjacent nodes on the dam–foundation interface. Consequently, a cantilever substructure is only coupled to adjacent substructures through the foundation rock.

3 PARAMETER STUDY

Morrow Point dam is a thin double curvature arch dam in a U–shaped canyon. The variable–center dam has an axis radius of 375 ft and the crest length is 724 ft. The thickness of the crown section varies from 52 ft at the base to 12 ft at the crest. Contraction joints between 18 cantilevers are spaced approximately 40 ft at the crest. The dam was selected for the parameter study because:

1. The dam is in a narrow canyon, so the arch action is important in resisting seismic loads.
2. The near symmetry of the dam makes it possible to analyze a symmetric half–model subjected to stream and vertical ground motion components.
3. Previous analytical and experimental studies of the dam are a good basis for interpreting the nonlinear earthquake response.

The parameter study investigates the response of a symmetric half–model of the dam to stream and vertical ground motion components. The response to static loads and symmetric ground motion is symmetric even with joint opening. Further investigation, not described in this paper, examines the effects of the cross–stream ground motion component on the entire dam, because the nonlinear dynamic response is not antisymmetric.

The symmetric half–model of Morrow Point dam includes four contraction joints evenly spaced along the radial direction. This corresponds to seven joints in a model of the full dam, spaced at 90 feet, compared with seventeen joints in the dam. The primary parameter investigated is the number of joints allowed to open in the half–model: zero, one, two, and four joints. For joints that are allowed to open, zero normal tensile strength is specified. Closed joints have a very large tensile strength that prevents opening.

The finite element model of the dam is based on nine design elevations to give 72 shell elements. Three joint elements are used through the thickness at each joint and the transition region has three solid elements in the arch direction. Energy dissipation is represented by Rayleigh damping of 5% in the first and fifth vibration modes. The static analysis includes self–weight and hydrostatic loads, but temperature effects are neglected.

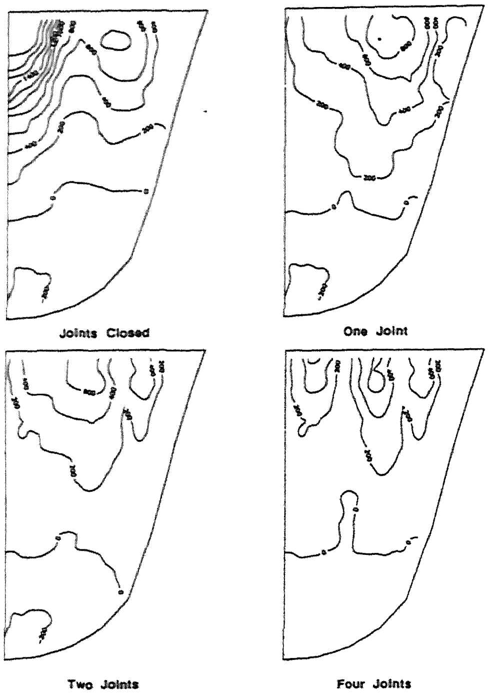
The finite element models of the full reservoir and foundation rock region are developed using the procedures described in Section 2.3.

The acceleration time history used as the input motion is characteristic of a maximum credible earthquake of magnitude 6.5 at a distance of one kilometer. The peak accelerations in the stream and vertical directions are 0.64 g and 0.39 g, respectively. Although the duration is twenty seconds, only the first twelve seconds are used because the peak response of the dam occurs within this time. The analysis uses a time step of 0.01 sec.

4 EARTHQUAKE RESPONSE

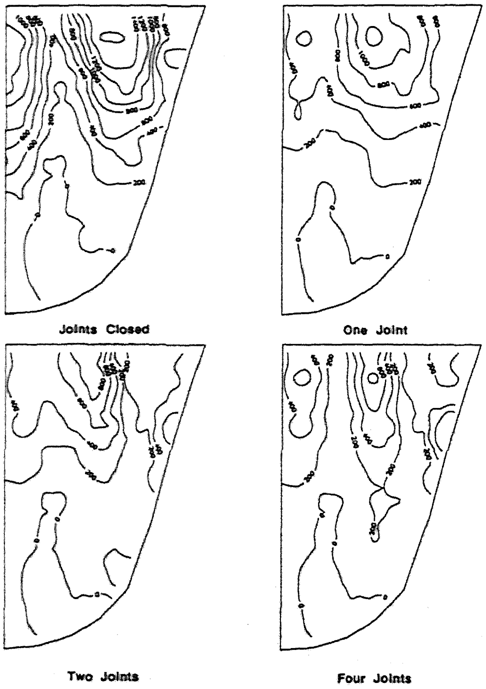
Figures 4 to 7 show the envelopes of maximum arch and cantilever stress at the upstream and downstream faces of the dam with full reservoir. The envelopes for the cases with zero (joints closed), one, two, and four joints in the half–model of the dam show the effects of contraction joint opening on stresses in the dam.

When the joints are prevented from opening (zero joints—the dam model is monolithic) the maximum arch tensile stresses are 2000 psi at the upstream face and 1600 psi at the downstream face. The maximum stresses occur at the crown section and at approximately the one–quarter point. Clearly, the contraction joints



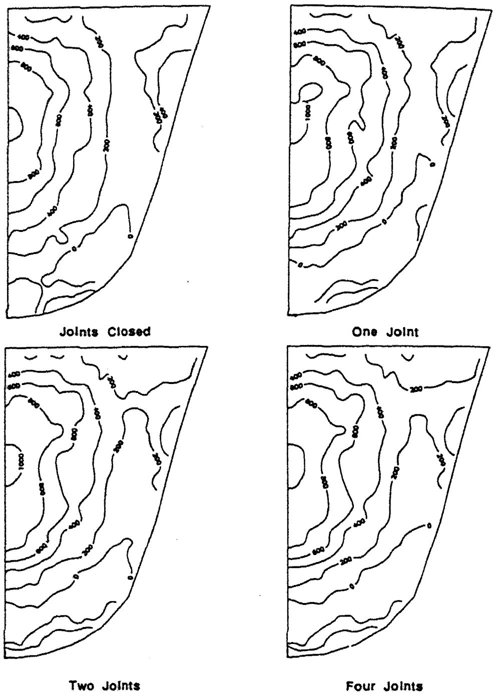
Joints Closed One Joint Two Joints Four Joints

Figure 4. Envelopes of maximum arch stress (in psi) at upstream face of dam with full reservoir.



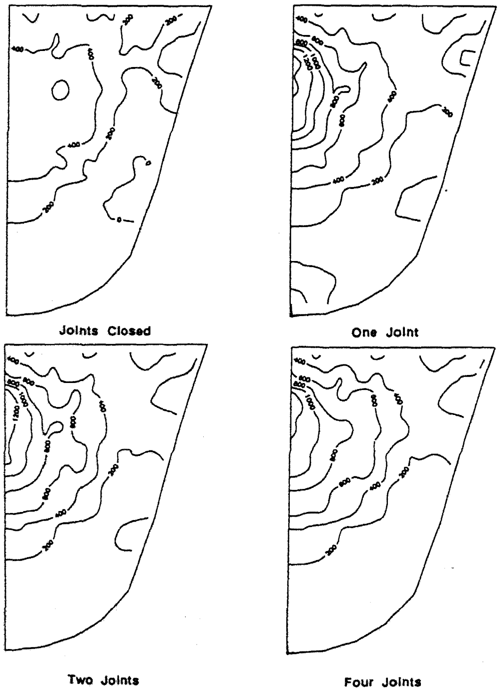
Joints Closed One Joint Two Joints Four Joints

Figure 5. Envelopes of maximum arch stress (in psi) at downstream face of dam with full reservoir.



Joints Closed One Joint Two Joints Four Joints

Figure 6. Envelopes of maximum cantilever stress (in psi) at upstream face of dam with full reservoir.



Joints Closed One Joint Two Joints Four Joints

Figure 7. Envelopes of maximum cantilever stress (in psi) at downstream face of dam with full reservoir.

cannot transmit the large tensile analysis predicted by a linear analysis.

Allowing one contraction joint at the crown section to open during the earthquake significantly reduces the arch stresses (Figures 4 and 5). With respect to the model with joints closed, the maximum arch stresses decrease from 2000 psi to 800 psi at the upstream face and from 1600 psi to 1200 psi at the downstream face.

The one contraction joint at the crown does not relieve the arch stresses of 1200 psi at the quarter-point of the downstream face (Figure 5). However, the model with two contraction joints reduces the arch tensile stresses in this region; the maximum arch tensile stress is 800 psi for the two joint model.

The final analysis includes four joints in the symmetric half-model of the dam. The four joint model has a maximum arch stress of about 800 psi and 600 psi at the downstream and upstream faces, respectively. The reduction in arch stresses from two to four joints is less than from one to two joints.

The history of arch stresses at the crown near the crest are shown in Figure 8 for the case with four joints (joints open) and zero joints (joints closed). The tensile stresses that develop in the monolithic model with no joints are eliminated when the joint is allowed to open. The effect of joint opening on the tensile stresses is more important at the upstream face than at the downstream face. The opening, however, does not alter substantially the maximum arch compressive stresses at these locations.

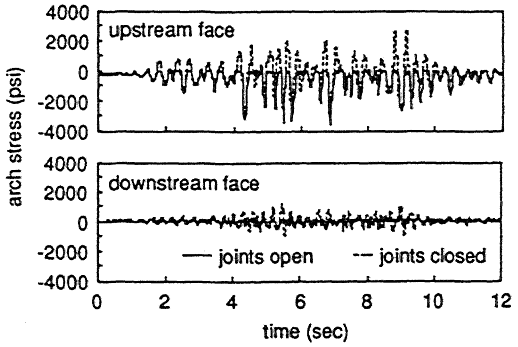


Figure 8. History of arch stress at crest of crown section of dam with four joints and full reservoir.

Joint opening has very little effect on the cantilever stresses at the upstream face. The maximum cantilever tensile stress is about 1000 psi for all cases (Figure 6). However, joint opening does affect the maximum cantilever stresses at the downstream face because the opening transfers the loads from arch action to cantilever bending in the upstream direction. The maximum downstream cantilever stress for the monolithic dam with no joints is 600 psi . As shown in Figure 7, this nearly doubles to a maximum of 1200 psi.

The joints open as the dam displaces in the upstream direction. Figure 9 shows the history of normal displacement at the crest of the crown joint for the four joint model. There are about 20 to 25 cycles of opening, and the maximum opening at the upstream face is one inch for the half-model, which correspond to two inches for the complete dam.

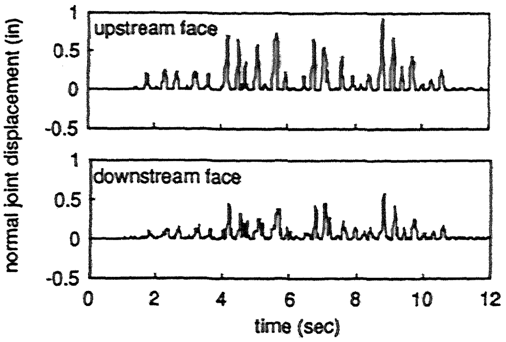


Figure 9. History of normal joint displacement at crest of crown section of dam with four joints and full reservoir.

5 CONCLUSIONS

The nonlinear earthquake analysis of a concrete arch dam with full reservoir shows that joint opening relieves arch tensile stresses typically computed by an analysis of a monolithic dam. For Morrow Point dam subjected to a maximum credible earthquake, the maximum arch stress reduces from 2000 psi to 800 psi when joints are allowed to open. As arch action is relieved, the cantilever stresses increase from a maximum of 1000 psi at the upstream face to a maximum of 1200 psi at the downstream face.

Based on the results of the parameter study, two joints for a half-model (three joints for a complete model) are the minimum necessary to represent the effects of joint opening in arch dams.

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