



Effects of perimetrical and vertical joint opening on the seismic response of a concrete arch dam

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Abstract

A three dimensional interface element is used to model the perimetrical and vertical joints in a concrete arch dam. This element is compatible with the complicated geometry of contact surfaces in concrete arch dams. During an earthquake, joint opening affects the seismic response of the dam by releasing the tensile stresses and redistributing the internal forces of the dam. When the joints open, the tensile stress can not develop across the joint and a tensile stress release occurs in that area. Although the opening mechanism of both perimetrical and vertical joint systems are the same but their effect on the response of the dam are different. Perimetrical joint opening at the contact area of dam-foundation, releases the cantilever tensile stresses at the base of upstream face and increases the radial displacement of the dam whereas vertical joint opening between the cantilevers of the dam releases the arch tensile stresses in dam body. After vertical joint opening, the dam has a tendency to displace toward upstream which results an increase in compressive cantilevers stresses at the base of upstream face.

1 Introduction

Concrete arch dams are not monolithic structures and contain variety of joints and discontinuities. Because the dam is constructed directly on bedrock, at the contact area of dam body and foundation there is an unavoidable system of joint named as perimetrical joint. Another joint system is the vertical joints between the cantilevers of the dam. During an earthquake these joints may open and close cyclically and redistribute the internal stresses in the dam. Linear dynamic analysis of concrete arch dams neglecting the effect of joints and discontinuities, results in high tensile stresses that cannot be interpreted with actual behaviour of the dam. One of the reasons for this inconsistency is the nonlinear response of the dam due to the presence of joints.

The importance of joint modeling in dam engineering has motivated several analytical and experimental researches. Clough [1] showed that vertical joint opening between cantilevers of the dam redistributes the internal forces and affects the seismic response of the dam by releasing the maximum arch tensile stresses. Fenves et al. [2], [3] investigated the effects of the number of joints on the seismic response of the dam and concluded that arch stresses reduce, as the number of joints in the model increase. However, there is a balance between the accuracy of the computed response and the amount of the computation required for the analysis. The results of the shaking table test of an arch dam model with and without joints done by H.Q. Chen et al. [4] and comparison with theoretical analysis using ADAP-88 program showed that opening of contraction joints under seismic loading reduces the arch tensile stresses and increases the cantilever compressive stresses and both shaking table test and finite element analysis produce similar results on this phenomenon.

In this paper a three dimensional curved isoparametric interface element, which is compatible with the complicated geometry of surfaces in contact, is used to model the perimetrical joints at the contact area of dam-foundation and vertical joints between the cantilevers of Shahid Rajaei arch dam in Iran and different effects of these two system of joints on the seismic response of the dam is investigated.

2 Nonlinear interface element

The interface element used to model the opening and closing of joints at predefined sections of the dam is shown in Figure 1. It consists of two 8 noded layers placed originally on top of each other with potential of being separated partially or completely. The element develops resisting forces due to relative displacement, but it does not develop inertial or damping forces. The relative nodal displacement $\{\Delta\rho\}$ can be expressed as differences between displacements of the top surface nodes of element A and bottom surface nodes of element B (Figure 1) through a difference matrix $[G]$ as,

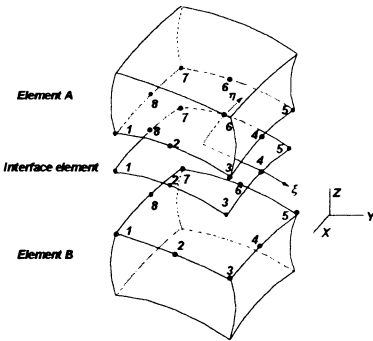


Figure 1- Interface element

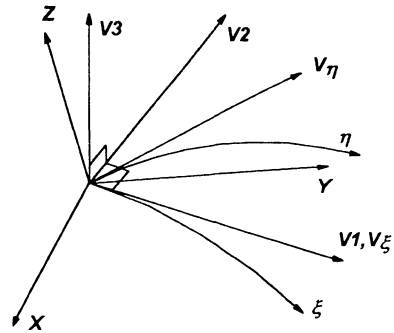


Figure 2- Global and local system at a point

$$\{\Delta\rho\} = [G]\{\rho\} \quad (1)$$

in which $\{\rho\}^T = \{u_1^B, v_1^B, w_1^B, \dots, w_8^B, u_1^A, v_1^A, w_1^A, \dots, w_8^A\}$ and $[G] = \begin{bmatrix} -I & I \end{bmatrix}$ with $[I]$ a 24×24 identity matrix. Defining the tangential and normal directions at any point of the interface with the help of unit vectors v_1, v_2 and v_3 (Figure 2) respectively, the relation between the stress and relative displacements at any point of the element in local coordinate system can be written as,

$$\{\sigma^e\} = [D^e]\{\varepsilon^e\} \quad (2)$$

in which

$$[D^e] = \begin{bmatrix} K_{s1} & 0 & 0 \\ 0 & K_{s2} & 0 \\ 0 & 0 & K_{s3} \end{bmatrix}$$

and K_{s1}, K_{s2}, K_{s3} are tangential and normal stiffness in directions v_1, v_2, v_3 . In the orthogonal local coordinate system, the assumption is made that displacement in direction i only produces stress in direction i . The surface relative displacement can be related to the global relative displacement as,

$$\{\varepsilon^e\} = [T]\{\varepsilon\} = [T][B]\{\Delta\rho\} \quad (3)$$

$$\text{in which } [T] = \begin{bmatrix} V_{1x} & V_{1y} & V_{1z} \\ V_{2x} & V_{2y} & V_{2z} \\ V_{3x} & V_{3y} & V_{3z} \end{bmatrix} \quad \text{and } [B_i] = \begin{bmatrix} N_i & 0 & 0 \\ 0 & N_i & 0 \\ 0 & 0 & N_i \end{bmatrix}$$

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V_{ix}, V_{iy}, V_{iz} are the x, y, z components of the unit vector V_i and N_i is the shape function associated with node i .

Using principles of virtual work, the stiffness matrix of the interface element is obtained in terms of the nodal displacements of the two surfaces in contact as,

$$[K] = [G]^T \left(\int_{-1}^1 \int_{-1}^1 [B]^T [T]^T [D^e] [T] [B] d(\text{area}) \right) [G] \quad (4)$$

A 3×3 Gauss quadrature is adopted for numerically computing the stiffness matrix.

3 Stress-relative relationship of interface element

The stress in interface element is a nonlinear function of relative displacement as shown in Figure 3. It has a limited tensile strength limit in normal direction. Below this limit the relationship is linear and once this limit is reached the joint unloads and subsequent tensile strength is zero. This behaviour is only in tension. In compressive stress state, the relation between stress and relative displacement maintains linear.

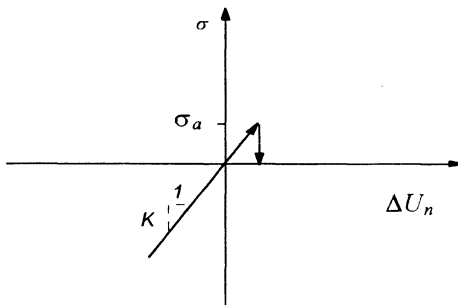


Figure 3- Stress-relative displacement relationship for interface element

4 Dam-reservoir interaction

The dynamic response of concrete arch dam is affected by interaction between the dam and impounded water. Considerable computation effort is required in evaluating the hydrodynamic terms (in the equation of motions of the dam) and in computation of dam response when effects of water compressibility and reservoir boundary sediments are included but this is not the objective of this paper. To simplify the dam-reservoir interaction, the conservative Westergaard approach is considered. In this method the hydrodynamic pressure, in excess of hydrostatic pressure, acting on the dam is proportional to the normal

acceleration of dam's upstream surface. Converting the effect of hydrodynamic pressure into equivalent nodal forces using principal of virtual work, leads to a virtual mass which is combined with the usual mass of the structure to consider the dam-reservoir interaction in a conservative manner. The effects of hydrodynamic pressure inside the perimetrical opened joints is not considered here and it is the future research plan of the authors.

5 Arch dam application

5.1 Finite element model

Shahid Rajaee is a parabolic arch dam (Figure 4) with the height of 133.5m and crest length of 420.0m. The thickness of the dam varies from 25.77m at the base to 6.96m at the crest of crown cantilever. The dam is a part of Shahid Rajaee project, located on the Tajan river in Tang-e-Soleyman gorge, near the city of Sari in north of Iran and it provides water supply for a vast rice-growing area. The construction and first impounding of the dam was finished in 1996.

The dam body is modelled with solid 20 noded isoparametric elements (Figure 5) and the perimetrical and vertical joints have been modelled with interface elements, shown in Figures 6,7. In perimetrical joint model the top and bottom surface nodes of interface element are connected to the solid elements of dam body and fixed foundation, relatively, and for the vertical joint

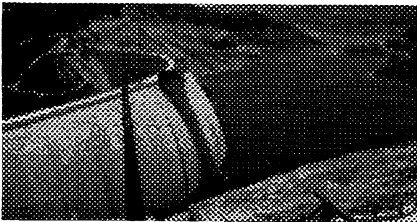


Figure 4- Shahid Rajaee arch dam

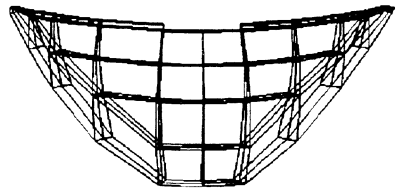


Figure 5- Finite element model of dam body

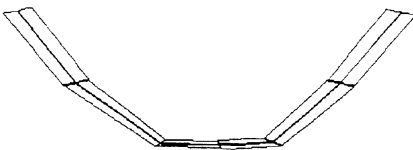


Figure 6- Finite element model of perimetrical joints

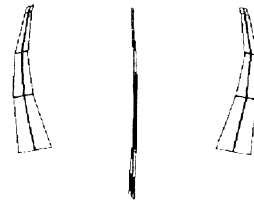


Figure 7- Finite element model of vertical joints

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model the top and bottom surface nodes of interface elements are connected to the nodes of solid elements of adjacent cantilevers.

5.2 Basic analysis parameters

The material parameters used for the dam body are [5]: Elastic modulus $E=30.0$ GPa., Poisson's ratio 0.18, Specific weight 2.4 T/m³, Uniaxial compressive strength 30.0 MPa., Uniaxial tensile strength 3.0 MPa.. Joint interface element parameters are: Elastic modulus 30.0 GPa., Tangential stiffnesses $K_{s1}=K_{s2}=0.2E$, Normal stiffness $K_{s3}=50.0E$., Tensile strength limit for perimetrical joint opening 1.5 MPa., Tensile strength limit for joint opening between cantilevers 0.0 MPa.. Only the first mode of opening (joint opening in normal direction of the surfaces in contact) is considered for both perimetrical and vertical joint systems. Water is supposed to be incompressible with weight density of 1.0 T/m³ and for perimetrical joint opening the water level is 122.0 m where for the vertical joint opening, minimum water level of 22.0 m (Low water level) is considered.

5.3 Loading

The loads applied to the model consist of static and dynamic loading. Dead weight and hydrostatic pressure are considered as static loads and dynamic load consists of three components of an earthquake, scaled for Shahid Rajaei dam site. According to the studies, the North Alborz fault, running near the site, has the most capable to create a strong motion with the magnitude of $M_s=6.9$ and the minimum epicenter of 5 Km below the dam.

Figure 8 shows three components of the earthquake which is applied at the same time on the dam with the maximum accelerations of $0.68g$, $0.58g$, $0.48g$ in EW (Upstream-downstream), NS (Left bank-Right bank), UD (Vertical) directions, respectively.

Temperature loads, silt load, tail water load and uplift are disregarded in the current analysis, however their effects should be considered in a complete safety evaluation. The static load is applied at negative time and the earthquake excitation starts at time zero. Hence, the effects of static loads are considered as initial condition for dynamic analysis.

6 Seismic response of the dam

6.1 Perimetrical joint opening

Figure 9 shows the time history of joint openings at the base of crown cantilever in 3 points through the thickness of the dam from upstream, figure 9(a), to down stream, figure 9(c), respectively. Maximum joint opening of about 11 mm

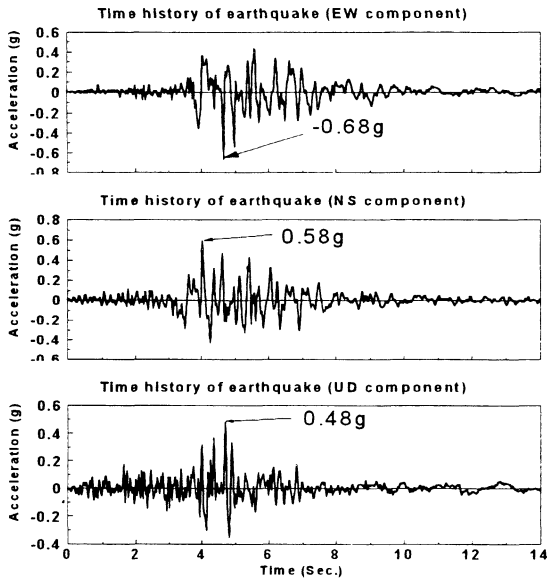


Figure 8- Three components of the earthquake in directions EW, NS, UD, respectively

occurs at time 4.36 Sec. on the upstream side and gradually vanishes to zero through the thickness of the dam toward downstream. Perimetrical joint opening at the contact area of dam body and foundation does not necessarily occur due to earthquake motion and even due to the static loading these joints may open. In figure 9, maximum joint opening of about 3.5 mm occurs at the base of crown cantilever on upstream side due to the combination of the hydrostatic pressure and dead weight of the dam. In figure 9 there is a permanent joint opening of about 4.5 mm on the upstream side but during the excitation it opens and closes cyclically.

Figure 10 compares the linear and perimetrical jointed time history of cantilever stresses at the base of crown cantilever from upstream to downstream side through the thickness of the dam. Due to joint opening, at the base of upstream face, there is a considerable cantilever tensile stress release. The agreement between the joint opening and stress release during static loading is also apparent in this figure. Figure 11 compares the linear and perimetrical jointed displacement response at the midheight of crown cantilever on upstream face in stream direction. As can be seen in this figure there is an increase in the displacement response of the dam for joint case and the dam has more tendency to displace toward downstream. Because of the joint opening, the stiffness matrix of the system concerning cracked interface elements is modified and a reduction in total stiffness matrix happens. This reduction, results an increase in displacement response of the dam.

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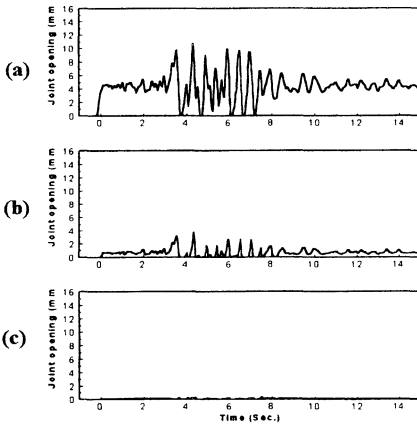


Figure 9- Joint opening at the base of crown cantilever from upstream to downstream face through the thickness of the dam

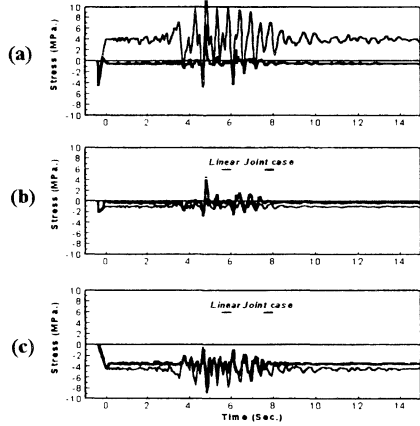


Figure 10- Time history of cantilever stress at the base of crown cantilever from upstream to downstream face

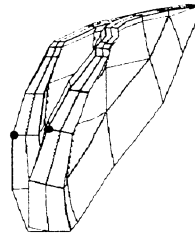
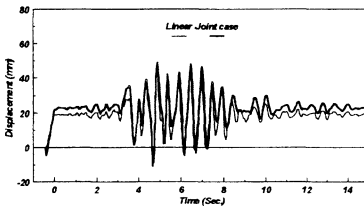


Figure 11- Displacement time history at the midheight of crown cantilever in stream direction

6.2 Vertical joint opening

Figures 12, 13 show the time history of joint opening and arch stresses at the midheight of crown cantilever on upstream face of the dam. A maximum joint opening of about 12.5 mm occurs on upstream face. The joint opening of about 2.5 mm has occurred due to the static loading and it remains in the dam at the end of excitation. A general joint closing also has happened between the times 4.2 Sec. and 8.5 Sec. respectively. Because of the vertical joint opening between two adjacent cantilevers, the arch tensile stresses can not develop across the joint and a tensile stress release occurs in that area. Figure 14 compares the displacement time history at midheight of crown cantilever in stream direction for linear and vertical joint models. Due to the joint opening between cantilevers, the dam has a tendency to displace toward upstream. In this case the arch action is lost and the cantilever action resists the internal forces by bending toward upstream which affects the cantilever stress distribution shown

in figures 15. Due to the above mentioned displacement tendency there is an increase in compressive cantilever stresses at the base of upstream face.

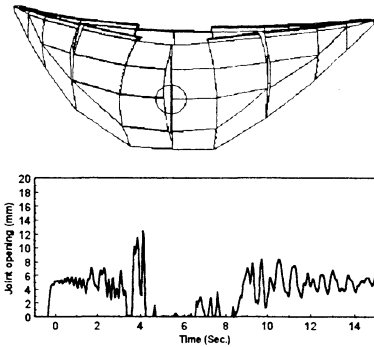


Figure 12- Vertical joint opening at the midheight of crown cantilever

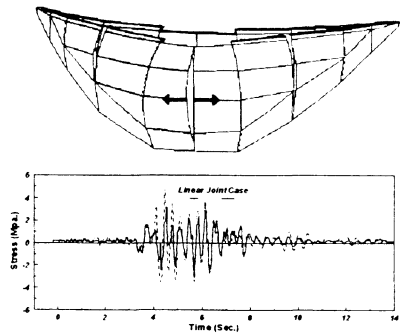


Figure 13- Arch stress at the midheight of crown cantilever on upstream face

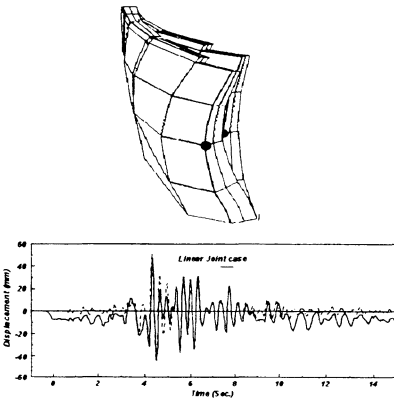


Figure 14- Displacement time history in stream direction

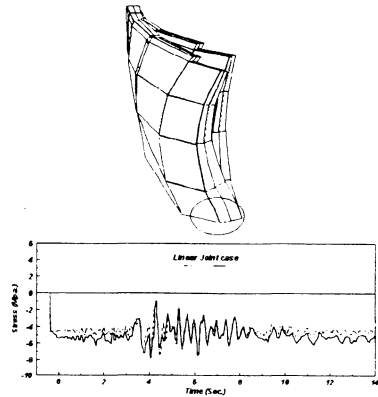


Figure 15- Cantilever time history at the base of upstream face

7 Conclusions

Using a three dimensional interface element to model the joints and discontinuities at predefined sections of an arch dam could solve, to some extent, the gap between linear dynamic analysis results and actual behaviour of the dam. Based on the results of the nonlinear joint analysis of Shahid Rajaee arch dam the following conclusions are obtained.

- Perimetrical joint opening at the contact area of dam body and foundation, specially at the base of crown cantilever, releases the tensile cantilever stresses and redistributes the internal forces of the dam.



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- When the perimetrical joints open, the dam has a tendency to displace toward down stream direction.
- Perimetrical joint opening occurs even during static load due to the presence of tensile stresses induced by high water level.
- Because of the vertical joint opening between two adjacent cantilevers, the arch tensile stresses can not develop across the joint and a tensile stress release occurs in that area.
- Contrary to perimetrical joint opening, when the vertical joints open, the dam displaces toward upstream which results an increase in cantilever compressive stresses at the base of upstream face of the dam.
- For both joint systems when the joints close, the dam regains it's stiffness and the response of the structure approaches the linear elastic case.
- Although the mechanism of both system of joints are the same but their effects on the response of the dam are different.
- Neglecting the effects of joints in the analysis of concrete arch dams may result high tensile stresses that can not be interpreted with the actual behaviour of the dam.

Acknowledgment

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