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Joint Opening Analysis of Concrete Arch Dams

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1. Introduction

Concrete arch dams are usually constructed as cantilever monoliths separated by joints. During an earthquake, because of low tensile strength, these joints may open and close cyclically and redistribute the internal forces in the dam. Linear dynamic analysis of concrete arch dams neglecting the effect of joints, usually results high tensile stresses that can not be interpreted with actual behavior of the dam. Relatively high cantilever tensile stresses at the base of crown cantilever and the arch tensile stresses on the upstream face of the dam are of this type. In this paper, perimetral joint opening at the contact area of dam body and foundation and vertical joint opening between cantilevers of the dam are of major concern. In order to model the joints at any predefined section of the dam a three dimensional isoparametric surface interface element with zero thickness is used. Nonlinear dynamic analysis of SHAHID RAJAEE arch dam in IRAN shows the effect of above mentioned mechanism on the response of the dam.

2. Finite element idealization and modeling

The interface element used to model the joints at predefined sections of the dam is shown in Fig. 1. It consists of two 8 nodded layers placed originally on op of each other with potential of being separated partially or completely. The relative nodal displacement of interface element can be expressed as differences between displacements of top surface nodes of element B and bottom surface nodes of element A. The element develops resisting forces due to relative displacement but it doesn't develop inertial or damping forces.

The stress in the joint element is a nonlinear function of relative displacement. It has a specified strength limit in the normal direction. Below this limit the relationship is linear and once this limit is reached the joint unloads and the subsequent tensile strength is zero.

For dynamic analysis the well known Newmark method have been used. The nonlinearity is due to presence of joints, modeled by interface elements at predefined sections of the dam. At each iteration the interface element is checked for tensile cracking and the stiffness matrix of the system concerning cracked gauss points is modified. As for the hydrodynamic pressure the Wetergaard approach has been used.

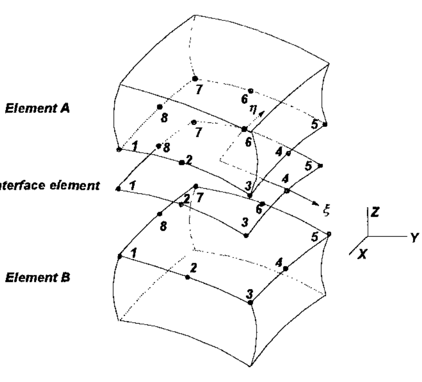

Fig. 1- Interface element

SHAHID RAJAEE is a parabolic arch dam with nominal height of 133.5m and crest length of 420.m located in the north of IRAN. The finite element model of the dam is presented in Fig.-2. The dam is modeled by 20 nodded isoparametric elements and 12 interface elements have been used to model the perimetral joint opening at the contact area of dam body and foundation. The top surface nodes of interface elements are connected to the nodes of dam body elements and the bottom surface nodes of the interface elements are fixed to the foundation. 24 interface elements have been used to model the vertical joint opening between cantilevers of the dam. The material properties used for concrete are: $\gamma = 2.4T/m^3$, $E_c = 30.0Gpa.$, $\upsilon = 0.18$, damping ratio 10% and for the joint element: $E_j = 30.0Gpa.$, tangential stiffness $K_{s1} = K_{s2} = 0.2E$ (in order to provide no slip condition), normal stiffness $K_{s3} = 50.0E$, tensile strength limit for vertical joint opening $\sigma_a = 0.$ Mpa., tensile strength limit for perimetral joint opening $\sigma_a = 1.5$ Mpa.. Only mode I of opening is considered for both perimetral and vertical joint opening. Two water levels, 95.m, 22.m are considered in computations.

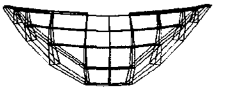

Fig.2- Finite element model of dam body

Keywords: Arch dam, Joint opening, Interface element, Perimetral joint, Vertical joint
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3. Earthquake analysis results

Fig. 3 represents time history of joint opening at the base of crown cantilever on U/S face. Maximum joint opening of about 6mm occurs at this point. Due to perimetral joint opening at this area there is a considerable vertical tensile stress release, relative to linear case, shown in Fig. 4. After joint opening, the stiffness matrix of the system concerning cracked interface elements is modified and a reduction in total stiffness matrix happens which results an increase in displacement response of the dam, specially in river and vertical directions (Figs 5,6). For vertical joint opening between cantilevers of the dam low water level, 22m, is considered. Fig. 7 represents time history of joint opening at mid height of crown cantilever with the maximum value of about 19mm. Since this value is less than depth of shear keys of the dam, the assumption of no slip condition for vertical joint opening is still valid. In Fig. 8 arch stress release due to vertical joint opening is shown and is compared with linear analysis results. When the joint closes, the structure regains it's stiffness and the response of the dam approaches the linear case. Due to vertical joint opening at low water level there is a tendency of displacement toward U/S as shown in Fig. 9. In this case the arch action is partially lost and the cantilever action resists the internal forces by bending toward U/S which results an increase in cantilever compressive stress at the base of U/S face and an increase in cantilever tensile stress at the base of D/S face, shown in Figs 10,11.

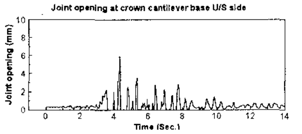

Fig.3- Time history of joint opening

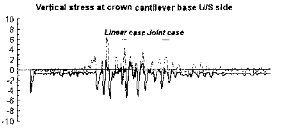

Fig. 4- Cantilever stress at base of crown cantilever on U/S face

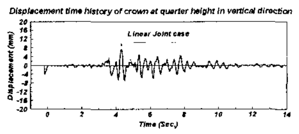

Fig.5- Displacement time history in vertical direction at quarter height of crown cantilever

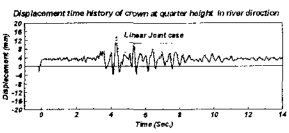

Fig. 6- Displacement time history in river direction at quarter height of crown cantilever

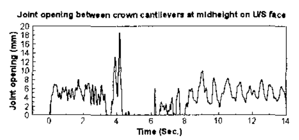

Fig.7- Time history of joint opening between crown cantilevers at midheight on U/S face

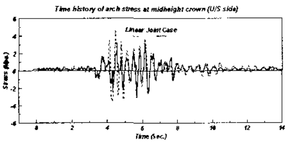

Fig.8- Time history of arch stresses at midheight of crown cantilever on U/S face

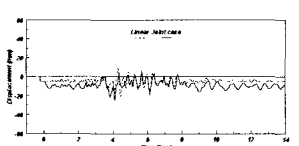

Fig.9- Displacement time history at midheight of crown cantilever in river direction

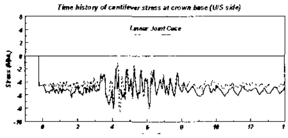

Fig.10- Cantilever stress time history at the base of crown cantilever on U/S side

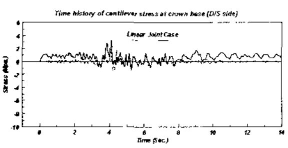

Fig.11- Cantilever stress time history at the base of crown cantilever on D/S side

4. Conclusion

Using the three dimensional interface element to model the joints and discontinuities in concrete arch dams relatively fills the gap between the linear analysis results and actual behavior of the dam.

- Vertical joint opening efficiently releases the arch tensile stress and redistributes the internal forces in the dam.
- When the vertical joint opens, the dam displaces toward U/S, the arch action is partially lost and the cantilever action resists the internal forces by bending toward U/S which results an increase in compressive cantilever stress at the base of U/S and an increase in tensile cantilever stress at the base of D/S face.
- After joint closing the dam regains it's stiffness and the response of the dam approaches the elastic case.
- Perimetral joint opening efficiently releases the cantilever stresses at the base of crown cantilever on U/S side of the dam.
- On the contrary with vertical joint opening, when the perimetral joint opens, the dam displaces toward D/S.

References

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