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EFFECTS OF JOINT OPENING AND MATERIAL NONLINEARITY ON THE SEISMIC RESPONSE OF A CONCRETE ARCH DAM

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SUMMARY

A three-dimensional curved surface isoparametric interface element is used to model the perimetral joints in the contact area of dam body and foundation and the vertical joints between the cantilevers of an arch dam. During an earthquake these joints may open and close cyclically and affect the seismic response of the dam. In this paper the nonlinearity of dam body material combined with nonlinearity due to presence of joints and discontinuities at predefined sections of the dam are investigated. Although the mechanism of both system of joints are the same but their effects on the response of the dam are different. Non-linear perimetral joint opening, releases the cantilever tensile stresses at the contact area of dam body and foundation and increases the compressive arch stresses at the midheight of crown cantilever. Non-linear vertical joint opening between the cantilevers of the dam releases the arch tensile stresses. In this case the arch action is partially lost and the cantilever action resists the forces by bending toward upstream face which results an increase in the cantilever compressive stresses at the base of upstream face. Considering the perimetral and vertical joint opening combined with the material nonlinearly of concrete to some extent fills up the gap between linear analysis results and actual behaviour of the dam.

INTRODUCTION

Concrete arch dams are not monolithic structures and contain variety of joints and discontinuities. Some of these joints are unintentional zones of weakness such as horizontal and vertical construction joints, concrete rock interface joints (Fig. 1) and others are designed to accommodate thermal strains, differential displacements and structural movements of the dam. During an earthquake these joints may open and close cyclically and affect the response of the dam. Linear dynamic analysis of concrete arch dams neglecting the effect of joints may result high tensile stresses that can not be interpreted easily. The importance of joint modelling in dam engineering has motivated several analytical and experimental researches.

[Dowling and Hall, 1989] developed a discrete joint model represented by non-linear springs. The earthquake analysis of Pacoima dam demonstrated that contraction joint opening, particularly in the upper portions of the joint, could occur even under moderate earthquake ground motions. The analysis of Morrow Point dam by [Fenves et. al, 1992] showed that the joint opening of the contraction joints has a significant effect on the stress developed in maximum credible earthquake. During an earthquake the contraction joints may open and close which result in arch tensile stress release and redistributing the internal forces between the arch action and cantilever action. They also investigated the effects of the number of joints on the seismic response of the dam and showed that arch stress reduce, as the number of joints in the model increase. They also demonstrated that modelling only a few numbers of joints in the arch dam is practical and can provide a realistic estimate of the stresses and displacements.

The results of the shaking table test with and without joints done by [H.Q. Chen et. al, 1996] 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 there is a good agreement between the experimental and theoretical results on this phenomena.

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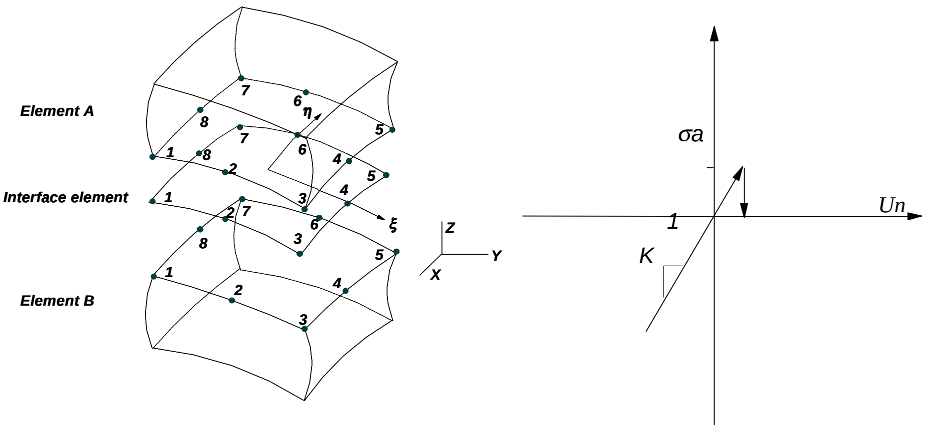
Fig.1- Perimetral and vertical joints in a concrete arch dam

There are many factors that contribute in the non-linear response of a concrete arch dam. Even if we model the joints and discontinuities at predefined sections of the dam, the assumption of linear stress-strain relationship for concrete under such a condition is not realistic and the material nonlinearity should be taken into account.

In this paper a three-dimensional curved isoparametric interface element is used to model the vertical joints between the cantilevers of the dam and the circumferential joint in the contact area of dam body and foundation. In order to model the material nonlinearity of concrete during loading and failure under three dimensional stress state, a comprehensive elasto-plastic fracture stress-strain relationship based on the theories of elasticity and plasticity is used and the response of a concrete arch dam considering the material nonlinearity combined with nonlinearity due to presence of joints and discontinuities at predefined sections of the dam is investigated.

CURVED INTERFACE SURFACE ELEMENT

Because of the complicated shape of contact area between the cantilevers of the dam and also the concrete-rock interface area, the quadratic isoparametric surface element [Buragohain D.N., Shah V.L., 1978] shown in Fig. 2(a) has been used to model the perimetral and vertical joints in a concrete arch dam. The element develops resisting forces due to relative displacements but it doesn't develop inertial or damping forces.



(a) (b)

Fig. 2- Joint interface elements

It consists of two 8 nodded surfaces with zero thickness, placed originally on top of each other with potential of being separated partially or completely. The top surface nodes of interface element are connected to the bottom surface nodes of element A and the bottom surface nodes of interface element are connected to the top surface nodes of solid element B to model the discontinuity between elements A and B. The stress in joint element is a non-linear function of relative displacement as shown in Fig. 2(b). It has a specified tensile strength limit. Once this limit is reached the joint unloads and the subsequent stress limit becomes zero. Below this limit the relation is supposed to be linear.

NONLINEAR ELASTO-PLASTIC DAM BODY MODEL

Considering the nonlinear material behaviour of dam body model, the tangential elemental stiffness matrix can be defined as

$$K_t = \int_v B^T D_{ep} B dv \qquad (1)$$

In which $D_{ep} = (D - \frac{Daa^T D}{A + a^T Da})$ (2)

is the elasto-plastic matrix, which depends on the yield surface taken and the assumptions being made, and B is the strain displacement transformation matrix. D is the elastic rigidity matrix and $a = \frac{\partial F}{\partial \sigma}$ named as flow vector and shows the direction of plastic strain. In this paper the Mohr-Coulomb model is used as

$$\frac{1}{3} I_1 \sin\phi + \sqrt{J_2}(\cos\theta - \frac{1}{\sqrt{3}} \sin\theta \sin\phi) = C\cos\phi \qquad (3)$$

$I_1, \sqrt{J_2}$ are the first and second invariant of the stress and θ is the angle of similarity and C, ϕ are the cohesion and angle of internal friction of the material. The flow vector can be written in the form of

$$a^T = \frac{\partial F}{\partial \sigma} = \frac{\partial F}{\partial I_1}\frac{\partial I_1}{\partial \sigma} + \frac{\partial F}{\partial \sqrt{J}}\frac{\partial \sqrt{J}}{\partial \sigma} + \frac{\partial F}{\partial \theta}\frac{\partial \theta}{\partial \sigma} \qquad (4)$$

Based on the above equations the elasto-plastic rigidity matrix and the tangential elemental stiffness matrix can be defined.

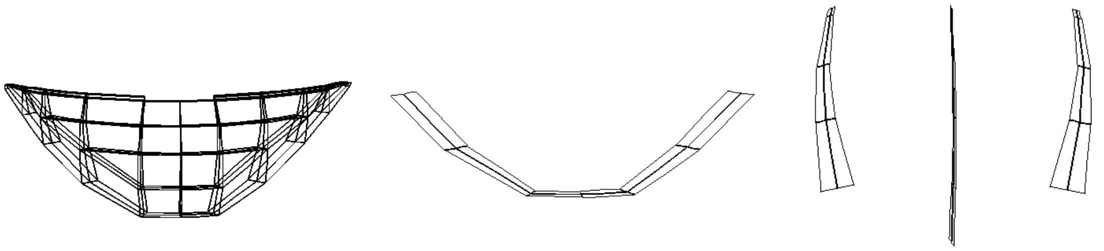
ARCH DAM APPLICATION

Finite element model

Shahid Rajaee is a parabolic arch dam with the height of 133.5m and crest length of 420.0m located in the north of IRAN. 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 Tajan river in Tange-Soleyman gorge near the city of Sari in the north of Iran. It provides water supply for vast rice-growing area and provision for a hydropower plant installation. Because the dam constructed directly on the bedrock at the contact area of dam body and foundation there is an unavoidable system of joint named as perimetral joint shown in Fig. 3-b. The top surface nodes of interface elements are connected to the solid elements of dam body and the bottom surface nodes of interface elements are connected to the fixed foundation. Fig. 3-c shows the finite element model of vertical joints between the adjacent cantilevers of the dam.

Basic analysis parameters

The material parameters used for the dam body are [Mahab Ghodss, 1996], elastic modulus 30. Gpa., Poisson's ratio 0.18, specific weight 2.4 T/m3, uniaxial compressive strength 30. Mpa., Uniaxial tensile strength 3. Mpa., cohesion 474. T/m2, angle of internal friction 54.9 degree. Joint interface element parameters are elastic modulus



(a) **(b)** **(c)**

Fig. 3- Finite element model of dam body, perimetral joint and vertical joint model

30. Gpa., tangential stiffness 0.2E, normal stiffness 50.E, tensile strength limit for perimetral joint 1.5 Mpa. and for vertical joint 0. Mpa..Water is supposed to me incompressible with weight density of 1. T/m3. For perimetral joint opening analysis the water level is supposed to be 122.m and for vertical joint analysis it is 22.m.

Loading

The load applied to the model consists of static and dynamic loading. Static loads are dead weight and hydrostatic pressure at high and low water levels. The loads applied to the model consist of static and dynamic loading. Static loads are dead weight and hydrostatic pressure at high and low water levels. The effects of temperature, silt load (sediment pressure), tail water load and uplift are neglected, however in a complete safety evaluation analysis these loads should be taken into account. Dynamic load consists of three components of Manjil earthquake scaled for Shahid Rajaee dam site with maximum accelerations of 0.667g, 0.579g, 0.482g in X, Y, Z directions (Fig. 4).

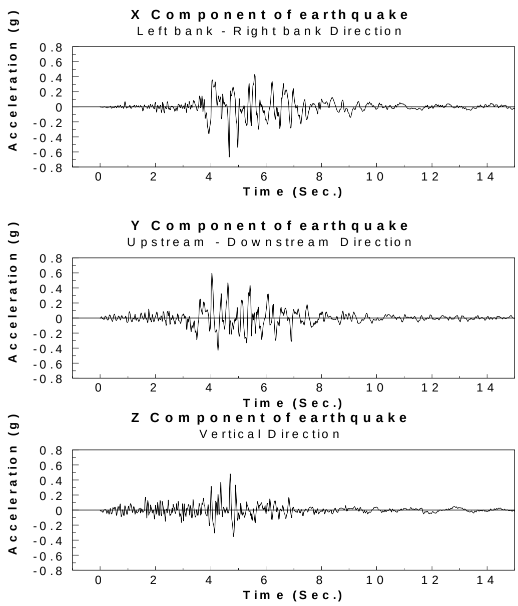


Fig. 4- Three components of earthquake in directions x, y, z

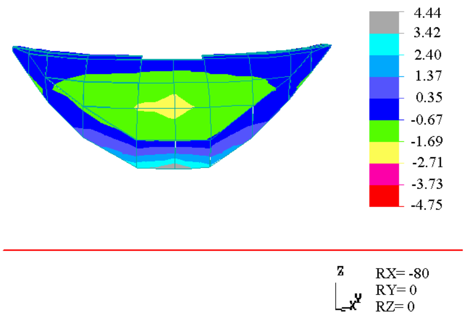
According to the studies, the North Alborz fault, running near the site has the most capable to create a strong motion with the magnitude of Ms= 6.9 and the minimum epicentre of 5 Km below the dam. Static loads are applied at negative time and dynamic loading starts at time zero, hence the effects of static loads are considered as initial condition for dynamic analysis. The static load is applied in 10 steps. At first the dead weight is applied in one step and after completion, the hydrostatic load is applied incrementally in 9 steps. After completion of static loads, at time zero the dynamic loading starts.

EARTHQUAKE RESPONSE OF THE DAM

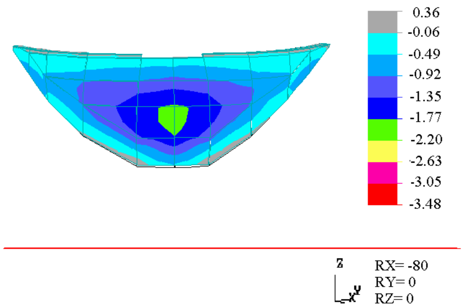
This section presents the earthquake response for the above mentioned models of Shahid Rajaee arch dam. The objective of the analysis is to investigate the effects of the nonlinearity due to presence of perimetral and vertical joints at predefined sections of the dam combined with non-linear behaviour of dam body material.

Perimetral joint opening

In this section the results of linear case are compared with the results of perimetral joint case and non-linear perimetral joint case. The difference between the perimetral joint case and non-linear perimetral joint case is that in the latter cases the material nonlinearity as well as joint nonlinearity is considered. Fig. 5 compares the cantilever stress contours of the dam at time 2 second for linear case and perimetral joint case. Due to the perimetral joint opening, maximum linear tensile stress of about 4.44 Mpa. at the base of crown cantilever on upstream side (Fig. 5-a) releases to about -0.06 Mpa. for the perimetrical joint model shown in Fig. 5-b which is a considerable tensile stress release at the contact area of dam body and foundation.Time history of joint opening at the base of crown cantilever is shown in Fig. 6. It consists of joint opening time history at the base of crown cantilever on upstream, centre and downstream face of the dam. Maximum joint opening of about 15 mm occurs at time 4.36 Sec. on the upstream side and gradually vanishes to zero through the thickness of the dam toward downstream face. Perimetral 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 Fig. 6, maximum joint opening of about 4.5 mm occurs at the base of crown cantilever on upstream face due to the combination of the hydrostatic pressure and dead weight of the dam. There is also a time lag in the first joint opening as a result of different stress states inside the thickness of the dam. In Fig. 6 there is a permanent joint opening of about 4.5 mm on the upstream side but during the excitation it opens and closes cyclically. This permanent opening vanishes to zero toward downstream face.



(a)



(b)

Fig. 5- Cantilever stress contours at time 2 second for perimetral (a) and linear case (b)

when the perimetral joints open, 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. Figs 7-a, b compare the linear and perimetral and non-linear perimetral jointed displacement time history at midheight of crown cantilever on upstream face in stream and vertical directions, respectively. Due to the above mentioned mechanism the dam had a tendency to displace toward down stream and upward directions after perimetrical joints open and there is an increase in maximum values of displacements in both directions. As can be seen in this figure when the effects of material nonlinearity are considered there is an increase in the displacement response and also residual displacement of the dam.

Vertical joint opening

Fig. 8 compares the arch stress results of the dam at time 2-sec. for both linear and vertical joint models at low water level. A maximum arch tensile stress of about 0.5 Mpa. at the central part of the crown cantilever for linear case, shown in Fig. 8-a, releases to about 0.06 Mpa. for vertical joint model in Fig. 8-b. At this instant of time maximum joint opening for the crown cantilever happen at midheight of the dam, where as for the left and right side cantilevers maximum joint opening occur at the crest of the dam. 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.

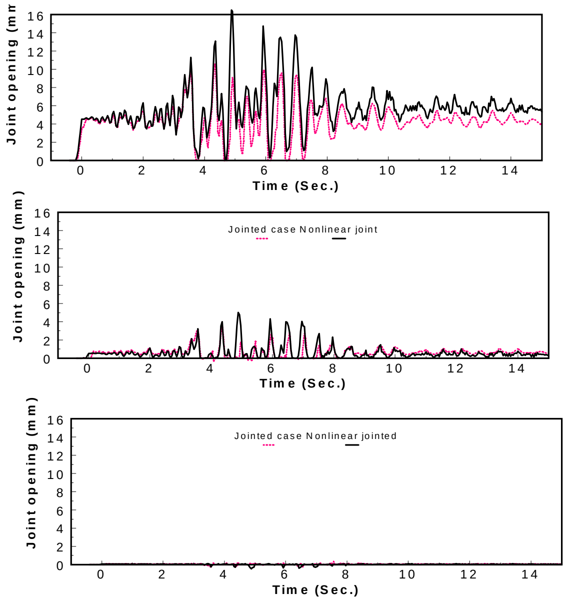
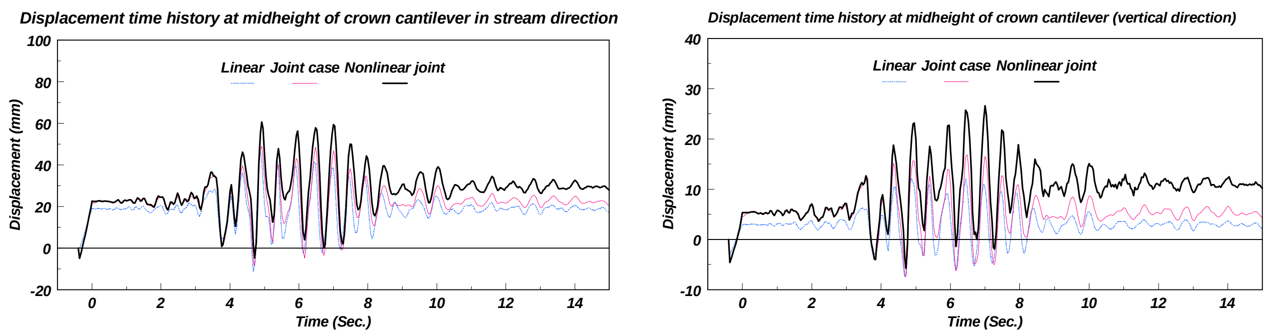


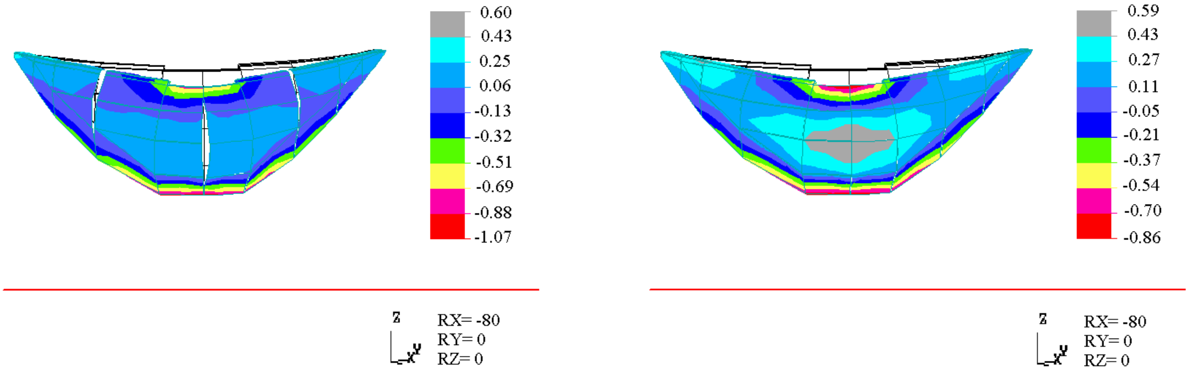
Fig. 6- Perimetral joint opening at the base of crown cantilever from upstream to downstream side



(a) **(b)**

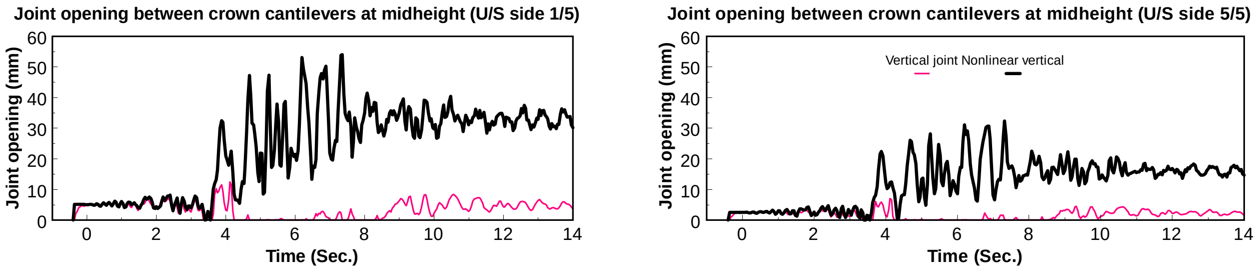
Fig. 7- Displacement time history at midheight of crown cantilever in stream and vertical directions

Time history of joint opening at the midheight of crown cantilever on upstream and down stream is shown in Fig. 9. Due to the concrete material nonlinearity there is a considerable increase in the joint opening and it propagates through the thickness of the dam. Maximum vertical joint opening of about 12.5 mm on upstream face increases to about 54 mm for the case of non-linear vertical joint model. There is also an increase in the permanent joint opening in non-linear vertical joint model. Fig. 10 compares the displacement time history at the crest 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. Due to the above mentioned displacement tendency, there is an increase in compressive cantilever stresses at the base of upstream face, shown in Fig. 11. Comparing Figs 10, 7 show that perimetral joint opening and vertical joint opening have different effects on the displacement response of the dam in stream directions. Although the joint opening mechanism for both system of joints are the same but their effects on the response of the dam are different. Based on the results of perimetrical joint opening at the contact area of dam body and foundation and vertical joint opening between the cantilevers of the dam and the results of the non-linear perimetral and vertical joint models, the following conclusions are obtained.



(a) **(b)**

Fig. 8- Arch stress contours at time 2 second for vertical joint (a) and linear case (b)



(a) **(b)**

Fig. 9- Vertical and non-linear vertical joint opening at midheight of crown cantilever on upstream (a) and downstream face (b)

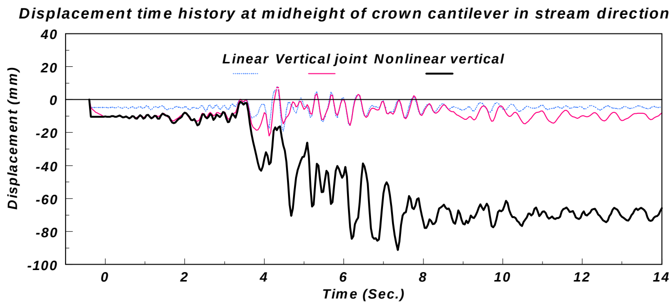


Fig. 10- Time history of displacement at midheight of crown cantilever in stream direction

CONCLUSION

Perimetral joint model

1- When the perimetral joints at the contact area of dam body and foundation opens, a cantilever tensile stress release occurs in that area and the dam resists the external forces by redistributing the internal stresses from cantilever action to arch action which results an increase in the arch compressive stresses on upstream face of the dam. 2- when the perimetral joints open, the dam has a tendency to displace toward down stream and upward directions. 3- Perimetral joint opening occurs even during static load due to the presence of tensile stresses induced by high water level. 4- Due to the material nonlinearity, the dam has more tendency to displace toward down stream side and upward directions and there exist a permanent displacement for the dam in both directions.

5- Due to the yielding of material and permanent displacement in the dam there is an increase in the maximum value of the perimetral joint opening at the base of crown cantilever.

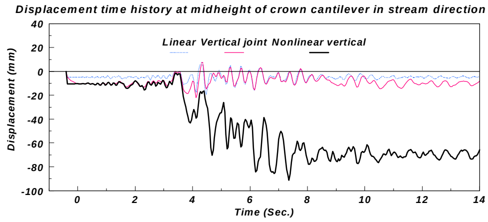


Fig. 11- Cantilever stress at the base of upstream face

Vertical joint model

1- 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. 2- Contrary to perimetral 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 and an increase in cantilever tensile stresses at the base of downstream face of the dam. 3- When the effects of the material nonlinearity is taken into account an increase in the displacement response of the dam occurs and maximum values of joint opening between the cantilevers of the dam increases. Since the maximum joint opening between the cantilevers is less than the depth of the shear keys of the dam there is no slippage between the adjacent cantilevers. 4- The joint opening response of the dam shows that there is no general joint closing in the non-linear vertical joint model and this is in agreement with the tensile arch stress release response at the same area. 5- in non-linear vertical joint model the dam has more tendency to displace toward upstream and downward directions and there is a considerable permanent displacement in both directions.

General conclusion

Dynamic behaviour of concrete arch dams during occurrence of strong motion was clarified by considering the joints and discontinuities at predefined sections of the dam and modelling the material behaviour of dam body. After joint opening, arch dam redistributes the internal forces by converting the cantilever action to arch action or vice versa. This process results in a stable stress state which is consistent with actual behaviour of the dam.

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REFERENCES

Chen, H.Q., and Yeh, C.Y., (1996) " Joint Opening of Arch Dam During Earthquake, Experimental and Analytical Results. " Institute of water conservancy and hydroelectric power research, Beijing, China.

Dhirendra N. Buragohain, Vasant L. Shah. " Curved isoparametric interface surface element, " Journal of Structural Engineering, ASCE Vol. 104, pp. 205-209.

Dowling, M.J., and Hall, J.F. (1989)." Non-linear Seismic Analysis of Arch Dams. ", J. Engrg., Mech., 115(4), 768-789.

Gregory L. Fenves, Soheil Mojtahedi and Richard B. Reimer. (1992) " Parameter Study of Joint Opening Effects on Earthquake Response of Arch Dams. " Report No. UCB/EERC-92/05 Earthquake Engineering Research Centre, University of California at Berkeley.

Mahab ghodss consulting engineers Tehran-Iran, Joint venture Stucky-Electrowatt, (1996) "Static and dynamic stress analysis of Shahid Rajaee arch dam, " CB/js/Report No. 4200/4104, Lausanne.