Effects of Joint-Movement on the Earthquake Response of Arch Dams

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ABSTRACT :

The earthquake observation at Pacoima arch dam revealed that during very strong earthquakes joint movement (joint opening in the normal direction and slippage along tangential direction) can take place. The weakening of dam integrity and possible damage to joint waterstops raised a safety concern to engineers. This is a kind of frictional contact problems characterized by highly nonlinear nature. In the conventional approach, an idealization of flat joint is assumed to simplify the solution, joint movement in the tangential direction is restricted to take into consideration the effect of shear keys. In order to obtain a better understanding of joint-movement phenomenon, three joint models were studied: (1) flat joints where free opening in the normal direction and free sliding in the tangential direction were allowed; (2) flat joints, only opening in the normal direction was allowed; (3) joints with a simplified shear keys. In this paper, a Nonlinear Non-Smooth Equation method with property of guaranteed convergence is employed to solve the frictional contact problems. Moreover, an implicit-explicit time integration scheme is employed to analyze the dynamic response of dam-foundation system subjected to earthquake excitation. The dynamic analysis of an arch dam with the first two joint models is performed by the proposed analysis approaches. And earthquake responses of the arch dam with rigid base for all three joint models are also analyzed by ANSYS. It was found, the stress distribution and joint openings of the first model is even more approaching those of the third model, because in the model of joints with shear keys, movement in the tangential direction may take place to some extent.

KEYWORDS: contraction joint, shear key, arch dam, earthquake response, nonlinear non-smooth

1. INTRODUCTION

More and more studies show that the opening, closure and sliding of contraction joints affect greatly the dynamic response of arch dams subjected to strong earthquke ground motion. Some methods to simulate the nonlinear contact problem resulted from the movement of contraction joints have been developed. One of the most widely used methods is the joint element based on penalty function[Fenves et al. 1992, Zhang Chuhan et al. 2000]. In the joint element, the opening, closure and frictional sliding can be modeled by defining a nonlinear constitutive model. Smeared approach [Hall, 1998] is also used to model the joints by incorporating the contact conditions of stresses at integration points. Some methods for solving frictional contact problem, such as penalty, Lagrangian multiplier and Augmented Lagrangian multiplier methods, can also be adopted to deal with contact-nonlinearities resulted from the joints. It is common practice in arch dams to have shear keys beveled or unbeveled at the contraction joints to transfer shear forces between two adjacent monoliths. The section of keys is so complicated which may be rectangular, trapezoidal and hemi-spherical, etc., and the number of keys is so much that it is difficult to simulate the real geometry accurately due to large computational cost. The effects of the shear key on the dynamic response of arch dam can be taken into consideration by two different models. In the first model, the joints' slippage is restricted and only joints' opening is allowed [Fenves et al. 1992]. And in the another model, the joint's slippage is allowed but in dependence on the shape of keys and the magnitude of opening of the joints[Lau et al. 1998]. For beveled keys, the slippage occurs when the joints open, while for unbeveled keys the slippage occurs when the magnitude of joint's opening exceeds the height of keys. Results of analysis [Lau et al. 1998] show that shear slippage across the contraction joints leads to very important changes in the displacement field and stress fields of an arch dam. In this paper, in order to investigate the effects of contraction joints and shear keys on the dynamic response of arch dams, a nonlinear non-smooth equation method as well as ANSYS are used to solve the frictional contact problem for contraction joints with different joint models.

2. ANALYSIS PROCEDURE FOR THE DAM-FOUNDATION SYSTEM WITH CONTRACTION JOINTS

2.1 Nonlinear Non-smooth Formulation of the contact problem resulted from the movement of contraction joints

The gradual opening, closure of the contraction joints and sliding along the joints' surfaces in case of the arch dam subjected to strong earthquake shock can be considered as a nonlinear contact problem. In this paper, a nonlinear non-smooth equation method proposed by Chen W.J. et al. 1996, Li X.W. et al. 2000 is improved to solve this problem.

The contraction joints are assumed to be flat, and node-to-node contact model is used. At every candidate contact points, a local coordinate system is defined as {n, a, b} where n represents the normal direction of contact surface and a, b represent the two orthogonal tangential directions in the contact surface. Some variables used for describing the contact constraints are as follows. P_n, P_a and P_t are the contact forces in normal and two tangential directions of contact surface. Δu_n, Δdu_a, Δdu_a are the normal gap and increments of relative displacement between two contact points along the two tangential sliding directions respectively. The system equilibrium equation and nonlinear non-smooth equations for contact condition are expressed by Eq.(1).

$$H = [H_1, H_2, H_3, H_4]^T = 0 \tag{1}$$

Where, H_1 is the dynamic equilibrium equation, , $H_2 \sim H_4$ are the frictional contact conditions formulated as a nonlinear non-smooth equations.

$$H_2 = \left[h_2^1, h_2^2, \ldots\ldots, h_2^{NC}\right]^T \tag{2a}$$

$$h_2^i = \min\left\{P_n^i, \Delta u_n^i\right\} = 0 \tag{2b}$$

$$H_3 = \left[h_3^1, h_3^2, \ldots\ldots, h_3^{NC}\right]^T \tag{3a}$$

$$\begin{aligned} h_3^i = \Delta d\tilde{u}_\tau^i + \min\left\{0, \mu \max\left\{0, P_n^i - \Delta u_n^i\right\} + \tilde{P}_\tau^i - \Delta d\tilde{u}_\tau^i\right\} + \\ \max\left\{0, -\mu \max\left\{0, P_n^i - \Delta u_n^i\right\} + \tilde{P}_\tau^i - \Delta d\tilde{u}_\tau^i\right\} = 0 \end{aligned} \tag{3b}$$

$$H_4 = \left[h_4^1, h_4^2, \ldots\ldots, h_4^{NC}\right]^T \tag{4a}$$

$$h_4^i = \Delta du_a^i \sin\tilde{\theta}^i - \Delta du_b^i \cos\tilde{\theta}^i = 0 \tag{4b}$$

$P_n, \tilde{P}_\tau, \tilde{\theta}$ are the contact forces in normal direction, tangential direction respectively and the angle of the resultant tangential force with the local a-direction; $\Delta d\tilde{u}_\tau$ is the increment of relative displacement along sliding direction. NC is the number of candidate contact pairs, the superscript 'i' denotes the i-th contact pair. Conditions (2), (3) and (4) are nonlinear complementary equations in nature. A generalized non-smooth damped Newton method is adopted for solving these non-smooth equations. The details of solution procedures and the theoretical proof on convergence property are described in reference [Qi, L.Q. and Sun J., 1993].

If a keying action produced by shear keys in the contraction joints is constrained such that relatively sliding is not allowed, then the contact conditions in the tangential direction represented by (3b) and (4b) should be replaced by the following ones.

$$H_2 = \left\{H_2^i\right\} = \left\{\Delta du_a^i\right\} = 0 \quad , i = 1,2,\ldots\ldots NC \tag{5}$$

$$H_3 = \left\{H_3^i\right\} = \left\{\Delta du_b^i\right\} = 0 \quad , i = 1,2,\ldots\ldots NC \tag{6}$$

2.2 Discrete impact and release conditions

During the process of joint opening, impact and release between two adjacent surfaces joints will occur, dynamic contact conditions on velocities and accelerations should be provided in addition to the Eq. (2), (3), (4) for static case, which are determined based on the equilibrium of kinetic energy and momentum. Discontinuities of contact velocities and accelerations may occur at the instant of initial impact, contact release and transition between stick and slip status. As R.L. Taylor et al. pointed out that these discontinuities can't be represented by the Newmark integration scheme. Modification for the velocities and accelerations of the contact nodes are performed based on the equilibrium of local momentum and kinetic energy with the velocities and accelerations determined by Newmark integration scheme. The detailed modifications can be found in Ref. [Lin and Hu, 2004].

2.3 Solution procedure for the dam-foundation system with contraction joints

Dam-foundation interaction also affects the dynamic response of the dam. In this paper, such effect is taken into consideration by the artificial Multi-Transmitting boundary (simply denoted as MTF) (Liao, Z.P. and Wong, H.L. (1984)) placed sufficient far away from the structure-foundation interface to model the outgoing wave (scattered motion) and the earthquake input. To deal with wave propagation problem, explicit time integration algorithm is preferable. For dynamic frictional contact problem, implicit time integration algorithm is suitable for enforcing the contact conditions more accurately. So the implicit-explicit transient algorithm proposed by Hughes T.J.R and W.K. Liu (Hughes T.J.R and W.K. Liu, 1978a,b) is employed for solving the dynamic equilibrium equations. The implicit-explicit algorithm combines the implicit Newmark algorithms and explicit predictor-corrector algorithms. Accordingly, the elements in the dam-foundation system are partitioned into implicit and explicit groups, so are the nodes. In the process of implementation, the elements in dam body and foundation are taken as implicit and explicit elements respectively, and then the nodes attached to implicit element are grouped with implicit nodes and the other nodes are grouped with explicit nodes. It should be noted that the artificial boundary nodes are assumed to be associated with the explicit elements, and the displacements, velocities of these nodes are computed by MTF. Quantities associated with nodes in the implicit, explicit groups and artificial boundary are denoted by the subscripts 'i', 'e' and 'b' respectively. Then the equilibrium equations of motion of the dam-foundation system are expressed in blocks as follows.

$$\begin{bmatrix} M_i & & \\ & M_e & \\ & & M_b \end{bmatrix}\begin{Bmatrix} \ddot{u}_i^{t+dt} \\ \ddot{u}_e^{t+dt} \\ \ddot{u}_b^{t+dt} \end{Bmatrix} + \begin{bmatrix} C_{ii} & C_{ie} & C_{ib} \\ C_{ei} & C_{ee} & C_{eb} \\ C_{bi} & C_{be} & C_{bb} \end{bmatrix}\begin{Bmatrix} \dot{u}_i^{t+dt} \\ \tilde{\dot{u}}_e^{t+dt} \\ \dot{u}_b^{t+dt} \end{Bmatrix} + \begin{bmatrix} K_{ii} & K_{ie} & K_{ib} \\ K_{ei} & K_{ee} & K_{eb} \\ K_{bi} & K_{be} & K_{bb} \end{bmatrix}\begin{Bmatrix} u_i^{t+dt} \\ \tilde{u}_e^{t+dt} \\ u_b^{t+dt} \end{Bmatrix} = \begin{Bmatrix} F_i^{t+dt} + R_c^{t+dt} \\ F_e^{t+dt} \\ F_b^{t+dt} \end{Bmatrix} \tag{7}$$

where M, C, K are matrices of mass, Rayleigh damping and stiffness respectively, R_c is the contact forces resulted from the contact of contraction joints.

In the dam-foundation system, the connection between implicit nodes and the nodes on artificial boundary does not exist, so $K_{ib} = K_{bi} = C_{ib} = C_{bi} = 0$. In equations (7), $\tilde{\dot{u}}_e^{t+dt}, \tilde{u}_e^{t+dt}$ are the predicted values of velocities and displacements for explicit nodes, and have the following form.

$$\tilde{\dot{u}}_e^{t+dt} = \dot{u}_e^t + dt \cdot (1-\alpha)\ddot{u}_e^t; \quad \tilde{u}_e^{t+dt} = u_e^t + dt \cdot \dot{u}_e^t + dt^2 \cdot (1-2\beta)\ddot{u}_e^t / 2 \tag{8}$$

where, α and β are the constants for Newmark integrator. Then $\dot{u}_e^{t+dt}, u_e^{t+dt}$ are obtained from the Newark expression.

$$\dot{u}_e^{t+dt} = \tilde{\dot{u}}_e^{t+dt} + dt \cdot \alpha \cdot \ddot{u}_e^{t+dt}; \quad u_e^{t+dt} = \tilde{u}_e^{t+dt} + dt^2 \cdot \beta \cdot \ddot{u}_e^{t+dt} \tag{9}$$

The first and second row in equilibrium equations of motion (7) can be expressed in the following form.

$$M_i \ddot{u}_i^{t+dt} + C_{ii}\dot{u}_i^{t+dt} + K_{ii}u_i^{t+dt} = F_i^{t+dt} - C_{ie}\tilde{\dot{u}}_e^{t+dt} - K_{ie}\tilde{u}_e^{t+dt} + R_c^{t+dt} \tag{10}$$

$$M_e \ddot{u}_e^{t+dt} = F_e^{t+dt} - C_{ei}\dot{u}_i^{t+dt} - K_{ei}u_i^{t+dt} - C_{eb}\dot{u}_b^{t+dt} - K_{eb}u_b^{t+dt} - C_{ee}\tilde{\dot{u}}_e^{t+dt} - K_{ee}\tilde{u}_e^{t+dt} \tag{11}$$

If the dynamic loads are induced by earthquake excitation, F_i^{t+dt} and F_e^{t+dt} vanish. The displacement and velocities of boundary nodes $\dot{u}_b^{t+dt}, u_b^{t+dt}$ can be obtained as the sum of the free-field motion and scattered motion from MTF.

The solution procedures of (10) and (11) for displacements, velocities and accelerations at time t+dt are described in Ref. [Lin and Hu, 2004].

3. SEISMIC RESPONSE OF AN ARCH DAM

In this section, the dynamic responses of an arch dam are calculated according to the procedure developed in Sec.2. Moreover, the effect of geometrical shape of shear keys which play important role in dynamic response of the arch dam are investigated by ANSYS with different joint models.

3.1 Seismic response of arch dam with contraction joints modeled by flat joint model

3.1.1 Assumptions, details of modeling, implementation

For simplification, it is assumed that water is incompressible and the hydrodynamic pressure of the impounded water acting on the dam face is evaluated by the Westergaard's added mass formula. The dam-foundation interaction is modeled by the artificial absorbing boundary based on the second order MTF, which simulates the outgoing scattered wave into infinite half space and also accounts for the spatially non-uniform seismic input.

In this section, the contraction joints are assumed to be flat and smooth. There are two kinds of flat joint models are taken into consideration. In the first flat joint model (simply denoted as FJA) the relative sliding between joints is allowed and a frictional coefficient is specified, and in the second flat joint model (simply denoted as FJB), the relative sliding between joints is constrained in order to consider the effect of shear keys.

3.1.2 Seismic response of arch dam

A 210m high double-curvature arch dam subjected to strong earthquake shaking is analyzed by the procedures proposed above. The finite element discretization of the dam-foundation system and layout of the contraction joints are shown in Fig.1. The maximum design accelerations are 0.5575g in the horizontal upstream and cross-stream direction and two third of 0.5575g in the vertical direction. The input ground accelerations time history are generated in accordance with the standard design response spectrum of China. The material of concrete and rock are assumed to be elastic, and the Young's modulus are 2.1e10Pa and 1.5e10Pa respectively, and the Poisson's ratios are 0.17 and 0.25 respectively. The water level is assumed 15m below dam crest.

The response results are selected to illustrate the differences between the two joint models. The envelope values of maximum principal stress on upstream surfaces are shown in Fig.2 and Fig.3 for joint models JFA and JFB respectively. The maximum openings along the axis of arch at dam crest are depicted in Fig.4. For both models, the values of tensile principal stresses on upper portion of the upstream face release to less than 1.5MPa due to joint opening, especially for joint model FJB in which slippage in joints is not allowed, the values of tensile principal stresses are lower than 0.5MPa on most part of the upstream face. The values of tensile stresses on most parts of downstream face are also less than 1.5MPa for both models. From Fig.4, it is seen that the maximum openings at the top of two end joints for model FJB are larger than those for model FJA, especially at top of the left bank joint. And there are no distinct differences for the gaps from B to P.

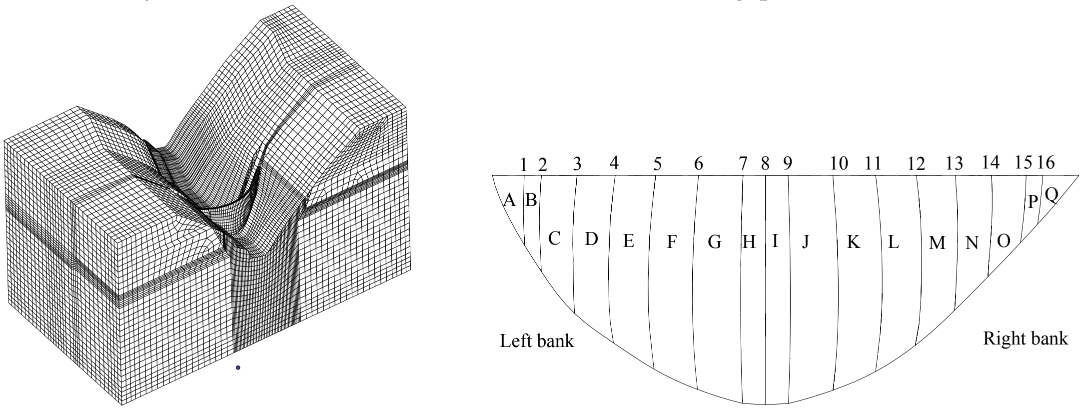
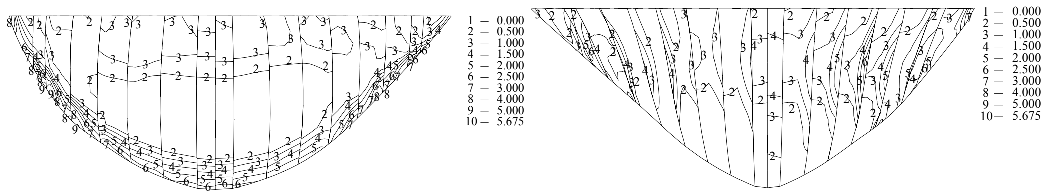
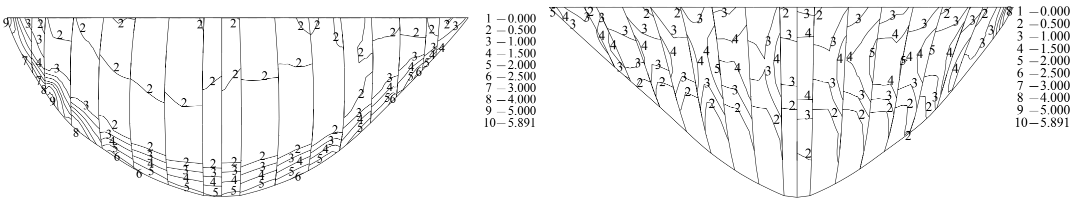


Fig.1 The finite element discretization of arch dam-foundation and the setup of contraction joints



(a) Upstream surface (b)Downstream surface

Fig.2 Envelop of Maximum principle tensile stresses on the dam surface (FJA, Unit:MPa)



(a) Upstream surface (b)Downstream surface

Fig.3 Envelop of Maximum principle tensile stresses on the dam surface (FJB, Unit:MPa)

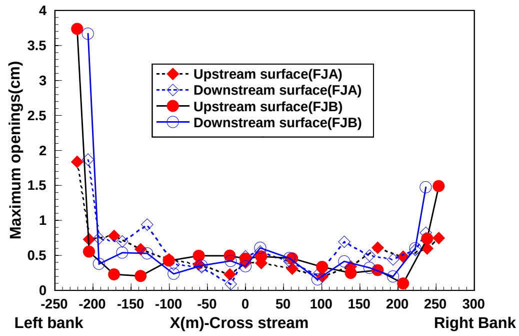


Fig.4 The maximum openings of the joints

3.2 Comparison of dynamic response for different joint models

ANSYS is also used to investigate the effects of the shape of shear keys on the dynamic response of the arch dam. In the analysis, three joint models are considered. A key structure joint model (simply denoted as KSM) is established and compared with the two joint models used in Sec.3.1. In the new model, a big shear key with 20cm-height rectangular section is used for modeling shape of shear key (Fig5). Because the realistic height of section is too small to be identified, the height of key section is magnified to show the position and shape of shear key in Fig.5. In the analysis, the foundation is assumed to be rigid and to simplify the computation, only 5 joints are taken into consideration. The input ground motions and water level are the same as those in Sec.3.1.

The envelope values of maximum principal stresses on upstream faces of the dam are shown in Fig.6~8 for three joint models. The maximum joint openings of the five joints on upstream and downstream faces at dam crest are given in Fig.10 for the three joint models. And the maximum slippages on upstream and downstream faces at dam crest are also shown in the figure, in which, for joint models FJA and KSM slippage is allowed.

For the flat joint models different base condition are considered, the values of tensile principal stresses on rigid base in Fig.6 and 7 are larger than those on flexible base in Fig.2 and 3. It is considered that the flexibility of base constraint and number of contraction joints affect the results.

From Fig.6 ~8, it is shown that the stress distribution and stress values are similar for the three models, especially for models FJA and KSM. Moreover the openings of joints and slippage for models FJA and KSM have similar distribution and values along the dam crest. The openings of joints for models FJA and KSM in different from those in Sec.3.1. It may be due to different foundation model used and different number of which slippage is allowed are larger than those for model FJB in which slippage is constrained. This result is contraction joints, further investigations are needed.

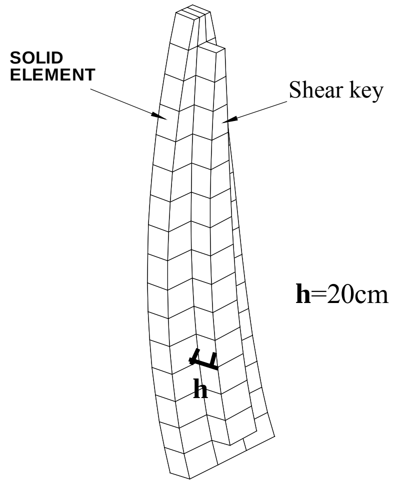
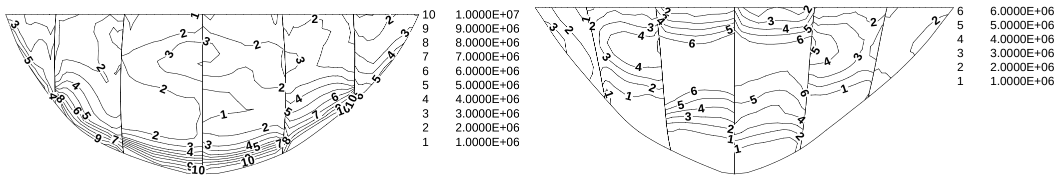
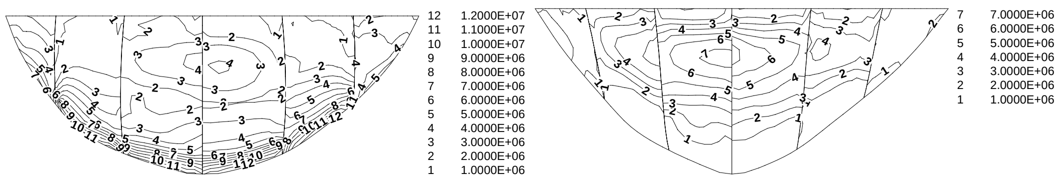


Fig.5 The key structure joint model with magnification of height of shear key



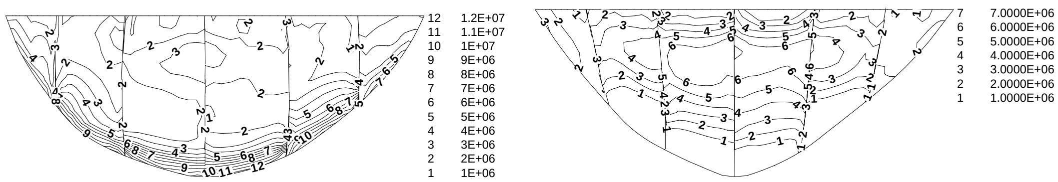
(a)Upstream surface (b) Downstream surface

Fig.6 Maximum values of maximum principle tensile stresses on the upstream(FJA, Unit: Pa)



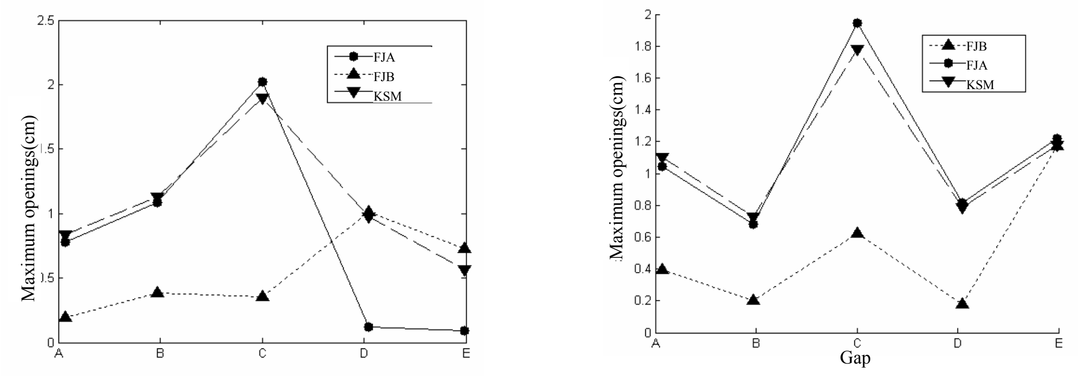
(a)Upstream surface (b) Downstream surface

Fig.7 Maximum values of maximum principle tensile stresses on the upstream (FJB, , Unit: Pa)



(a)Upstream surface (b) Downstream surface

Fig.8 Maximum values of maximum principle tensile stresses on the upstream(KSM, Unit:Pa)



(a) Upstream (b)Downstream

Fig.9The maximum openings of the joints at the top of arch dam

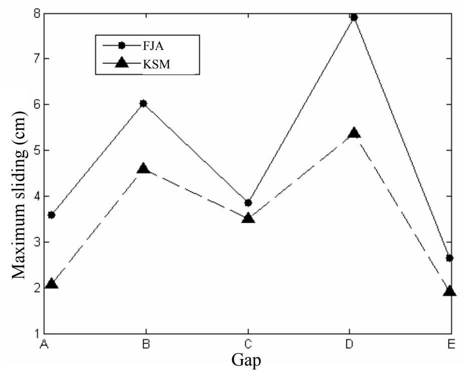


Fig.10 The maximum sliding of the joints at the top of arch dam

4. Conclusion

In this paper, an analysis procedure for the study of contact non-linearities resulted from the contraction joints and dam foundation interaction is proposed. Dynamic analysis of an arch dam is performed and the effects of geometrical shape of shear keys on the dynamic response of arch dam are also investigated. Numerical results lead to the following conclusions.

1. In the analysis procedure, the effects of contact non-linearities resulted from the opening, slippage of contraction joints and the dam-foundation interaction on dynamic response of arch dam can be taken into consideration. In the non-linear non-smooth equation methods, the contact conditions on the amplitude of displacement and contact forces are satisfied accurately and those on conservation of momentum and kinetic energy at the instant of impact and release are also taken into account approximately. The non-uniform earthquake input at the dam-foundation interface and the scattered wave propagation in the infinite half space can be taken into consideration by the artificial boundary conditions expressed by Multi-Transmit-Formula.

2. When the radiation damping of unbounded foundation is accounted for, the stresses values on the dam faces become considerably small than those for rigid base. And the more the number of contraction joints is simulated, the more the stresses values on dam surfaces decrease.

3. For dam model with flexible base, values of maximum tensile principal stress on dam faces decrease considerably due to the opening of contraction joints. The joint openings for model FJB are larger at the dam crest of two end joints than those for model FJA.

4. From the results with different joint models by ANSYS, the stress distribution, the joint opening and slippage are similar for joint models FJA and KSM in which the slippage is allowed. For the joint model FJB in which the

slippage is prevented, the joint opening is less than those for model FJA and KSM.

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