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NONLINEAR SEISMIC RESPONSE ANALYSIS OF XIAOWAN ARCH DAM WITH CONTRACTION JOINT

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SUMMARY

A comprehensive study of nonlinear seismic response of the Xiaowan arch dam with contraction joint has been conducted. A numerical model of contraction joint[Fenves et al.,1989] is used to simulate the contraction joints of a 292-meter high arch dam--the Xiaowan arch dam. Several parameter studies such as critical element size and required number of joints to be modeled for convergence are also performed. The results demonstrate that the joint opening and corresponding load transfer between the arch and the cantilever components of the dam during strong earthquakes are substantial. Maximum joint opening always occur in the central portion of the dam and the magnitude of the contraction joint opening is strongly influenced by the distance interval between adjacent joints in simulation. Therefore, all contraction joints along the central portion of the dam must be taken into account in the analysis to obtain accurate results of the maximum joint opening while fewer joints need to be simulated beyond the central portion of the dam resulting in little effects on the maximum joint opening. However, the number of joints need be simulated can be significantly reduced if only the stress distribution of the dam is of interest.

INTRODUCTION

The prototype performance of the Pacoima arch dam during the 1971 San Fernando earthquake was an example of contraction joint opening of arch dams in strong earthquakes[Hansen and Roehm, 1979]. A residual joint opening of 10mm at the crest and extending downward about 16m emerged in the contraction joint between the thrust block and the dam monolith. From this experience, it appears that the contraction joint opening of arch dams during strong earthquakes is inevitable and will be an important factor in safety evaluation of arch dams. Due to this nonlinear behavior, weakening of dam integrity and possible damage of waterstops between joints raise a safety concern to engineers when joint opening exceeds a certain degree. Meanwhile, although the release of arch constraint due to joint opening yields a reduction of tensile stresses in arch component, the increase of cantilever stresses may lead to horizontal cracking. It may be desirable to control the joint opening so that an idealized stress distribution between the arch and the cantilever components can be reached.

Problems of such non-linearity of arch dams were first raised by [Clough, 1980]. [Dowling and Hall,1989] presented a 2-D discrete joint element for simulation of gradual opening and closing of joints of 3-D arch dams in an approximate manner. The nonlinear analysis of the Pacoima dam subjected to the 1971 San Fernando earthquake is performed as a case study. [Fenves, Mojtahedi and Reimer, 1989] used a 3-D nonlinear joint element and an efficient numerical procedure for solving this problem. The F.E. substructure technique is employed by considering the set of joint elements as a single nonlinear substructure while the cantilevers between joints as linear ones and their degrees of freedom can be condensed out. A typical arch dam-Big Tujunga was analyzed using the presented method. [Zhang, Xu and Jin, 1998] combined the effects of dam-canyon interaction into the nonlinear behavior of arch dam, thereby describing the influence of canyon radiation on nonlinear dam response.

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As a preliminary study of seismic control of arch dams, the nonlinear response of a 292m high arch dam with contraction joint is studied in this paper. The feasibility and method of joint opening control of arch dams are being studied and will be published in the future. Herein, the analysis by the revised program of ADAP-88 shows that the magnitude of the joint opening is strongly influenced by the distance interval between adjacent joints, and the opening of contraction joints has substantial effects on the seismic response of arch dams.

BRIEF INTRODUCTION OF XIAOWAN ARCH DAM

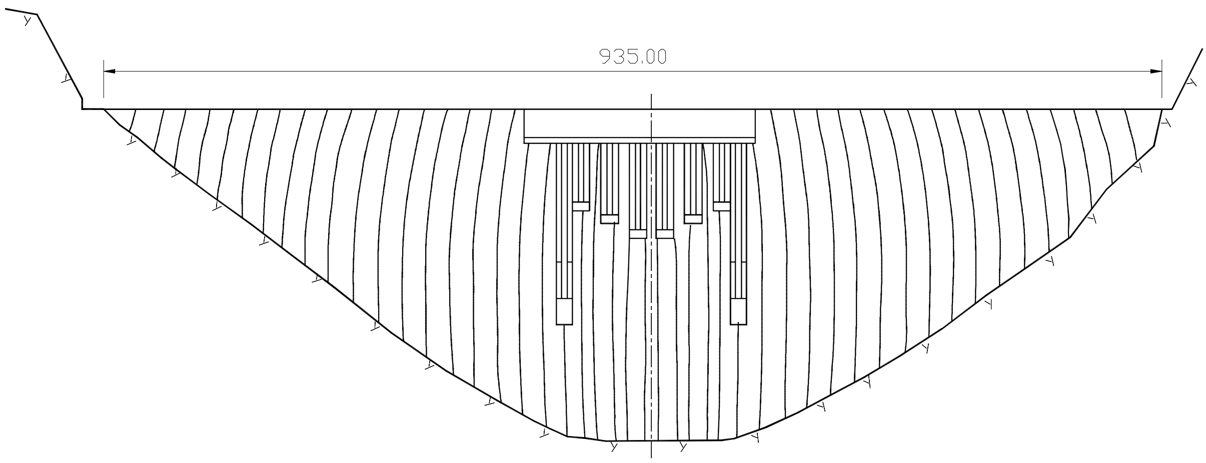


Figure 1: Layout of contraction joints of the Xiaowan Arch Dam

Shown in Figure 1 is the layout of the Xiaowan arch dam. It is located on the upper reaches of the Lanchang River, Yunnan province under the stage of preliminary design. The canyon is of V-shape type and the dam has a crest length of 935m. The maximum dam height is 292m. The thickness of the dam is 69m at the bottom and 13m at the crest. 48 contraction joints are to be grouted during the construction of the dam. The peak accelerations of the design basis earthquake are: PVA=0.308g in two horizontal directions and 2/3 PVA in the vertical direction. The material properties for the concrete are: mass density = 2400kg/m^3, modulus of elasticity $= 2.0\times10^4$ MPa, Poisson′s ratio=0.18; for the foundation rock: mass density=0, modulus of elasticity $= 2.73\times10^4$ MPa, Poisson′s ratio=0.25. Computational tests are conducted for examination of convergence and accuracy of the results versus the mesh size of the element and the number of contraction joints to be simulated.

3. STUDIES ON CONVENGENT PARAMETERS

Since the Xiaowan arch dam is a 292m high and has a 920m crest length. Convergent tests are needed be performed for determination of element size and number of joints to be simulated.

3.1 Number of Mesh Elevation Layers for Convergent Response

In dynamic finite element analysis, the effects of mesh size of elements on the convergent response need to be considered. For the revised program of ADAP-88, the mesh size of elements is closely related to the number of mesh elevation layers. Herein, four cases, namely: 9,11,12 and 13 elevation layers are selected for comparison. For the reason of computational economy, only 5 contraction joints equally located along the crest are simulated as the nonlinear substructure. The convergence of the response and the joint opening are shown in Figures 2 and Figure 3. It is concluded that 12 elevation layers give convergent results in terms of displacements and joint opening. The maximum stresses show very similar tendencies of convergence indicating that 12 elevation layers are sufficient to obtain accurate results. The maximum mesh size is 30m in this case.

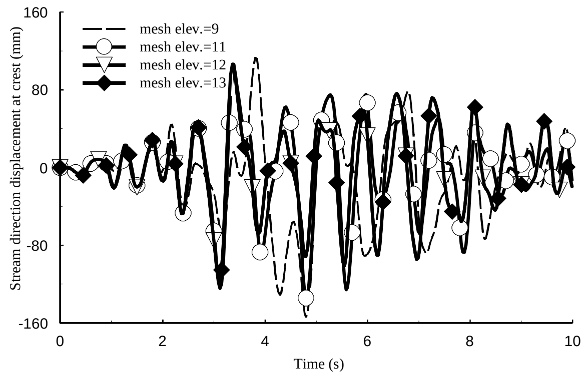


Figure 2: Convergence of Displacements

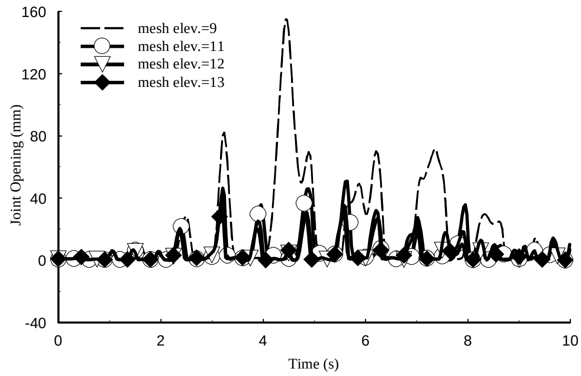


Figure 3: Convergence of Joint Opening

3.2 Number of Joints to be Simulated for Convergent Response

As shown in Figure 1, in reality, 48 joints are designed for dam construction. For computational economy, fewer joints may need to be simulated in the analysis. Herein, seven cases of joint number simulation are assumed for comparison, i.e. 1, 3, 5, 7, 9, 21 and 25 joints without considering the initial strength of the grouting material. Figure 4 shows the layout of 25 joints case which has approximately design distance of nearby joints(≈20m) along the central portion of the dam and a double design distance of nearby joints(≈40m) along other part of the dam. For all other cases the joints are equally spaced beside the crown cantilever. So the joints named L_{1a}, L_{2a}, R_{1a} and R_{2a} are not modeled in the 21 joints case. In these convergent tests, the design basis earthquake and the lowest reservoir elevation are chosen as load conditions for analysis.

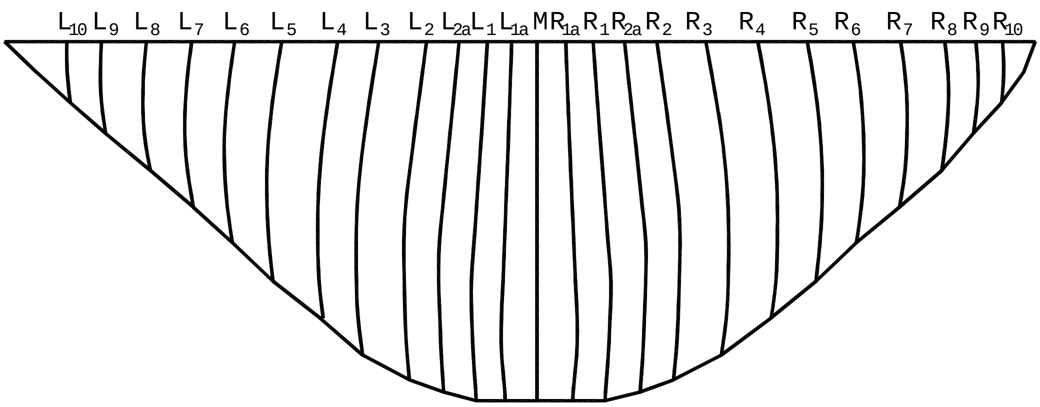
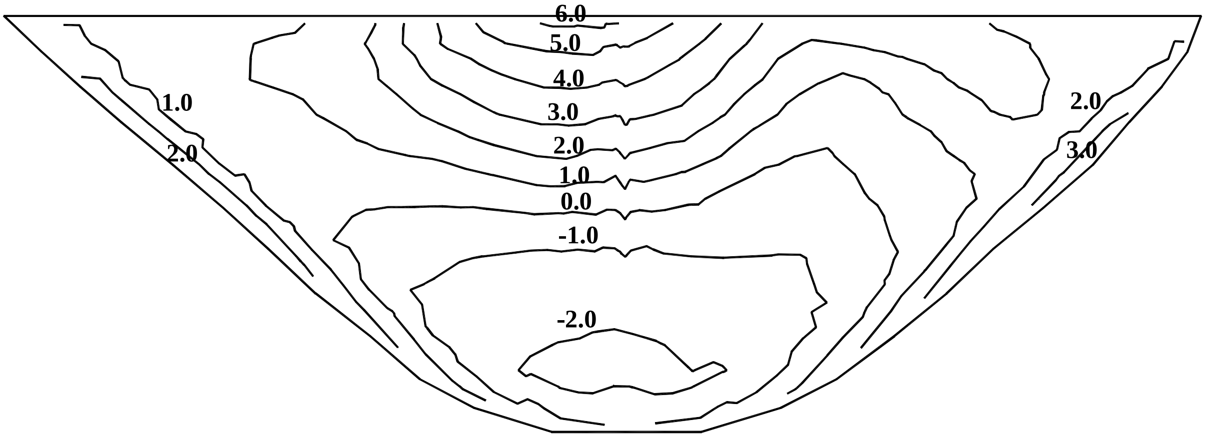
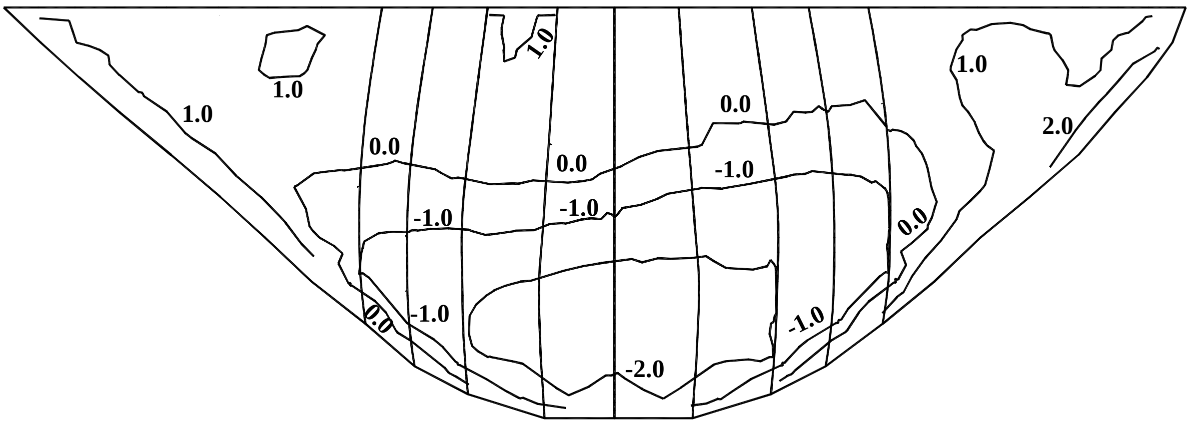


Figure 4: Simulation of Contraction joints for Xiaowan Arch Dam (Case of 25 Joints)

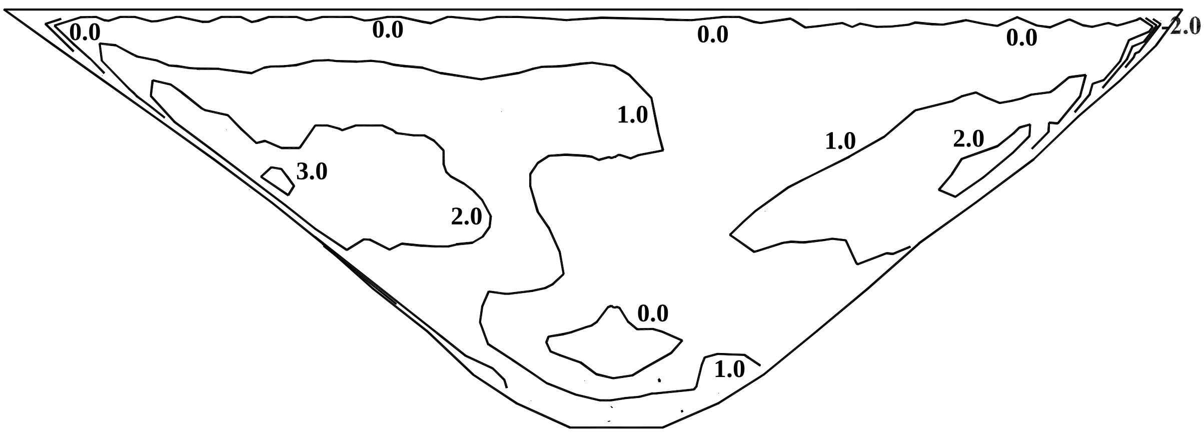


(a) Maximum stress of arch component on upstream face(without joints)

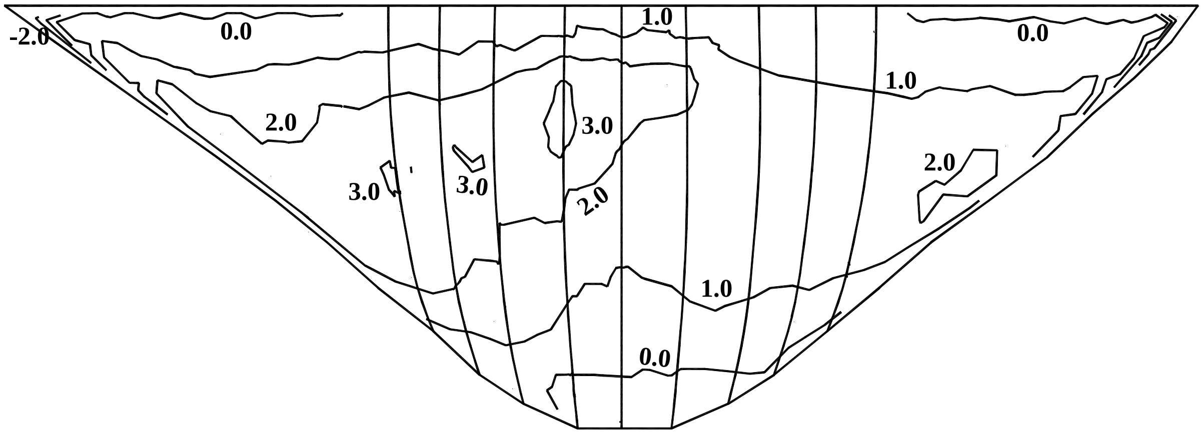


(b) Maximum stress of arch component on upstream face(with joints)

(c)



(c) Maximum stress of cantilever component on downstream face(without joints)

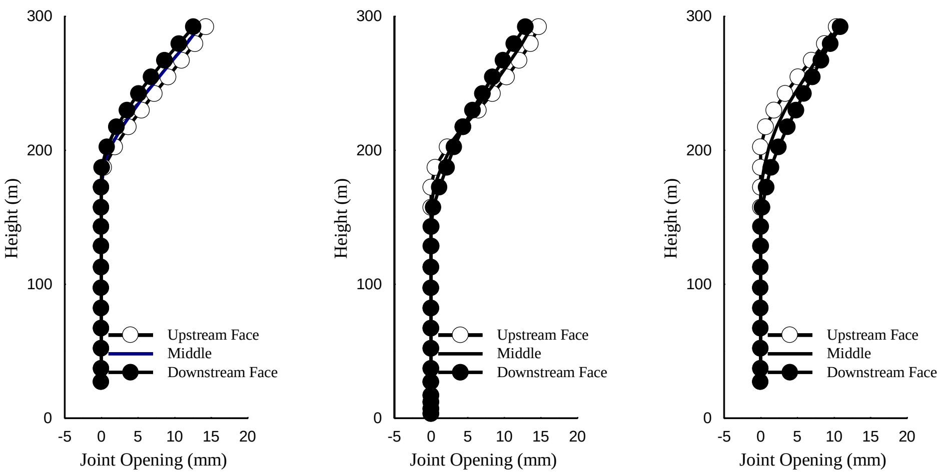


(d) Maximum stress of cantilever component on downstream face(with joints)
Figure 5: Comparison of the Maximum Stress Isolines With and Without Contraction Joints

Table 1: Maximum joint opening of left portion of Xiaowan Arch Dam

Case	Number of joints	L_{10}	L_9	L_8	L_7	L_6	L_5	L_4	L_3	L_2	L_{2a}	L_1	L_{1a}	M
1	1													84.4
2	3											55.0		20.6
3	5									25.4		29.8		25.9
4	7								8.5	18.6		27.0		25.5
5	9							5.6	6.6	16.6		23.8		25.2
6	21	0.2	2.9	3.9	5.7	6.1	3.0	3.7	4.6	12.7		26.9		26.9
7	25	1.1	3.9	5.3	7.1	6.5	5.5	6.2	8.5	10.6	14.3	14.3	15.1	14.7

Because of symmetry, only maximum joint opening of left portions are listed in Table 1. It is interesting to note the following: (i) The openings of joint M in different cases(comparisons between case1 and case 2, case6 and case7) show that the maximum opening of the joint is strongly influenced by the distance interval of adjacent joints. So, the magnitude of joint opening can only be obtained accurately if the distance interval of adjacent joints in the simulation equals to the real design situation;. (ii) The largest opening of joints always occurs in the central portion of the dam, thus requiring a complete simulation of each joint in this portion. (iii) By comparison of the maximum stress isolines for all cases (only maximum arch stresses on upstream face and cantilever stresses on downstream face of case 5 are shown in Figure 5 for space limitation), significant release of the arch action for all cases except the case 1 resulting in very similar stress fields in arch component is evident. On the other hand, noticeable differences of the cantilever stresses near the side joint area are observed indicating the effects of the side joint opening are of minor influence. As the stress distribution is concerned , nine joints(case 5) may be sufficient in the analysis ignoring the stress differences in side joint regions because the tensile stresses in the upper central portion of the dam are of most importance in dynamic situation. (iv) Figure 6 shows the maximum joint opening at the instance of maximum response of the dam under the lowest reservoir elevation. It is evident that the upper middle portion of the joints experiences complete opening from upstream to downstream faces. Antisymmetric patterns of the opening between the left and the right joints imply the significant contribution by the cross-stream excitation.



(a) Joint L2a **(b) Joint M** **(c)Joint R2a**

Figure 6: Joint Opening of Xiaowan Arch Dam at Instant of Maximum Opening

4.EFFECTS OF GROUTING AND WATER LEVEL ON SEISMIC RESPONSE

To demonstrate the effects of contraction joints on the dam response, different conditions are assumed in the analysis:

(i) Initial grouting strength: 1/4 tensile strength of concrete and zero strength;
(ii) Reservoir conditions: full and lowest operation reservoir elevations;

4.1 Effects of initial strength of grouting on response

To study the effect of initial strength of joint grouting on seismic response of dam, an additional case is 21 joints with initial strength of the grouting material being 1/4 tensile strength of concrete. the comparisons shown in Table 2 demonstrate that the initial strength of the grouting material contributes nothing to the joint resistance of the dam and needs not be considered in the analysis.

Table 2: Maximum joint opening of cases with and without initial strength of grouting (mm)

Initial strength of grouting	L_{10}	L_9	L_8	L_7	L_6	L_5	L_4	L_3	L_2	L_1	M
1/4 tensile strength of concrete	0.2	2.9	3.9	5.7	6.1	3.0	3.7	4.6	12.7	26.9	26.9
0	0.2	2.9	3.9	5.7	6.1	3.0	3.7	4.6	12.6	26.8	27.0

4.2Effects of water level

Maxmimum tensile stress level of central portion of dam in 9 joints case are listed in Table 3. Since the openings of joints of full operation resevoir elevation are much smaller than that of lowest operation resevoir elevation, only the later is listed in Table 1.

Some conclusion can be drawn: (1) The opening of joints under full operation reservoir level is much smaller than that under lowest operation reservoir level due to the compression of water load. (2) The stress of arch component under full operation reservoir elevation decrease less significantly than that under lowest operation reservoir elevation because of the opening of contraction joints. (3) In the case of without contraction joints, maximum tensile stress is 6MPa, which is the stress of arch component under lowest operation reservoir level. When contraction joints considered, maximum tensile stress decrease to 4MPa, which is the stress of cantilever component under full operation resrevoir level. So, the joint opening and corresponding load transfer between the two components of the dam during strong earthquakes are substantial.

Table 3: Maximum tensile stress level of central portion of dam (MPa)

Water Level	Linear analysis without contraction				Nonlinear analysis with contraction			
	Up-Arch	Dn-Arch	Up-Cant.	Dn-Cant	Up-Arch	Dn-Arch	Up-Cant.	Dn-Cant
High	3.0	2.0	3.0	4.0	1.0	1.0	4.0	4.0
Low	6.0	4.0	2.0	1.0	1.0	2.0	2.0	3.0

Notes: Up(Dn)-Arch(Cant.) means maximum tensile stress level of arch (cantilever) components on up(down) stream faces along central portion of the dam.

Water level high(low) means full(lowest) operation reservoir elevation

5. CONCLUSIONS

Nonlinear seismic response of arch dams due to contraction joint opening has been studied comprehensively. The important aspects of the subject are possible deterioration of the structure integrity and significant transfer of sustained loads from the arch to cantilever component, resulting in a substantial release of arch tensions, while, on the other hand, a significant increase in cantilever stresses. Contraction joint reinforcement may be a measure for joint opening control and the load transfer balance between the arch and cantilever components, and thus is being studied. Conclusions can be drawn from the preliminary analysis.

(1) The procedure is applicable to the nonlinear analysis of arch dams due to contraction joint opening;

(2) In the case of the Xiaowan arch dam under the given load conditions and design parameters, the maximum joint opening can reach 15mm for design basis earthquake. Substantial load transfer from the arch components to cantilever elements is observed especially on the upper middle portion of the dam. Joint opening control may be necessary for resisting strong earthquakes;

(3)In order to obtain the maximum opening of the joints more accurately, all the designed contraction joints in the central portion of the dam need to be simulated . However, the number of joints need be simulated can be significantly reduced if only the stress distribution of the dam is of interest.

6. ACKNOWLEDGEMENTS

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REFERENCES

Hansen, K.D. and Roehm L. H. (1979), “The response of concrete dams to earthquake”, *Water power and dam construction*, pp27-31.

Clough, R. W. (1980), “Nonlinear mechanisms in the seismic response of arch dams”, *Int. Research conf. on earthquake eng.*, Skopje, Yugoslavia.

Dowling , M. J. and Hall, J. F. (1989), “Nonlinear seismic analysis of arch dams”, *J. Eng. Mech. Div. ASCE*, 115, pp768-789.

Fenves, G. L., Mojtahedi, S. and Reimer, R. B. (1989), “ADAP-88: A computer program for nonlinear earthquake analysis of concrete arch dams”, *Report No. EERC 89-12*, Earthquake Engineering Research Center, University of California, Berkeley, CA.

Zhang, C. H., Xu, Y. J. and Jin, F. (1998), “Effects of soil-structure interaction on nonlinear response of arch dams”, *11th European Conference on Earthquake Engineering*, Balkema, Rotterdam.