DAMAGE SIMULATION OF HIGH ARCH DAMS IN EARTHQUAKES

H. Zhong[1], G. Lin[2] and H. J. Li[3]

[1] *Doctor, Earthquake Engineering Research Division, Dalian University of Technology, Dalian. China*
[2] *Professor, Earthquake Engineering Research Division, Dalian University of Technology, Dalian. China*
[3] *Post doctor, Dept. of Engineering Mechanics; Dalian University of Technology, Dalian. China*
Email:gaolin@dlut.edu.cn, zhonghongm@126.com

ABSTRACT :

A numerical approach based on elastic damage mechanics is presented to simulate the crack evolution and damage mode of arch dams subjected to earthquake shocks. The initial inhomogeneity of concrete at the mesoscopic scale is idealized with stochastic distribution of material properties of finite elements. Each element in the dam is considered to be homogenous and obeys simple constitutive relations of brittle concrete materials. When the elements reach the assumed failure criteria-Mohr-Coulomb Principle with tension cut-off, its elastic modulus is reduced to a sufficiently small value.
Based on domain decomposition method, the proposed approach is programmed to parallel finite element codes PDPAD with MPI (Message Passing Interface) in FORTRAN 9.0 on Linux Redhat 9.0. The verification of a to-be-built arch dam in China shows that cracks in concrete are caused mainly by excessive tensile stress. Cracks initiated at the top of the central cantilever and were distributed at the vicinity of the dam crest, with the rest of dam remained intact. Numerical simulation obtained similar results with shaking table test, indicating that the proposed procedure and corresponding parallel program PDPAD could efficiently simulate seismic damage mode of arch dams.

KEYWORDS: seismic damage, mesoscopic inhomogeniety, parallel computing, arch dam

1. INTRODUCTION

China is one of the richest countries in the world in hydro-power potential, with its 378*103MW exploitable capacity developed by only 22%. With the implementation of Western Development Strategy and West-East Power Transmission program, many high arch dams are under construction or will be constructed in the southwestern part of China. As is known that this region is seismically active, dams are subjected to high risk of earthquakes, which could result in heavy loss of human life and substantial property damage. The accuracy of the risk evaluation associated with these dams is highly dependent on a proper understanding of their behavior due to earthquakes.
In conventional design methodology of concrete dams, linear dynamic analysis is employed to obtain the maximum tensile stress, which is then compared with the so-called tolerable stress of concrete to evaluate the safety of dams. However, the tolerable stress is generally exceeded and crack would initiate in the dam. In the last decades, researchers have made progress in considering the crack propagation utilizing two approaches. One approach uses fracture mechanics concept to model the discrete cracks observed in plain concrete. It has the potential to determine accurately the geometry of every single crack. It requires complete details of the initiation and propagation of cracks within the dam, and when the crack surface changes, the domain needs to be remeshed, which could be extraordinarily computational expensive. Therefore, the application of fracture mechanics is limited to problems where only a few well-defined fractures are expected. For large-scale problems such as high arch dams, owing to the complexity of 3D problems, it becomes excessively complicated. Up to now, no research has been reported concerning the application of fracture mechanics to 3D arch dams. Another approach is the continuum damage mechanics. Damage mechanics provides an average measure of material degradation due to microcracking, interfacial debonding, nucleation and coalescence of voids. For quasi-brittle materials such as concrete, damage is regarded as the stiffness degradation. This material degradation is reflected in the nonlinear behavior of dams. When the crack profiles are not known *a*

priori, this approach turns out to be computationally effective. Since it models the effect of cracking via an average procedure, it can not precisely predict the failure process of dams. In addition, further investigation needs to be conducted concerning cyclic loading and anisotropic materials.

On the whole, much progress has been made regarding the nonlinear analysis of concrete dams subjected to earthquakes, but most of these work focused on 2D analysis of gravity dams. For example, Koyna dam in the 1967 Koyna earthquake has been investigated by many researchers (Valliappan et al (1996), Ghrib et al (1995), Lee et al (1998)). Much less work was devoted to arch dams subjected to earthquakes though. Among them: Valliappan et al (1999) developed a damage model for brittle materials exhibiting strain-rate-dependent fracture behavior and predicted possible damage area of an arch dam. Lotfi et al (2004) presented a combined discrete crack and smeared crack technique, and investigated the nonlinear dynamic behavior of a thin arch dam. Chen et al (2003) used a damage model exhibiting strain-rate-dependent behavior to examine the nonlinear response and possible damage area of an arch dam. Cui et al (2002) employed 3D rigid body-spring element method to simulate the continuous failure of Meihua arch dam. Pan et al (2007) used a plastic damage model to analyze the cracking of Dagangshan arch dam, taking into consideration the softening behavior of tensile strain.

It is important to point out that concrete is assumed to be homogeneous in the above models. However, as it's universally accepted that concrete is a composite consists of coarse and fine aggregates, cement hydrates, unhydrated cement gradules, micro-cracks and voids on the mesocopic level. Heterogeneity is a basic characteristic for concrete. Since it wasn't considered properly in conventional analysis of concrete structures, some important behaviors such as crack propagation and failure process of those structures were not modeled sufficiently. By taking into account of heterogeneity, we can possibly obtain new insights into the nonlinear behavior of concrete structures. In the material failure process analysis(MFPA) of Tand et al (2002), concrete is assumed to be a three-phase composite composed of matrices, aggregates and matrix-aggregate interfaces, and elements of each phase are assumed to conform to Weibull distribution. This model was applied to simulate crack propagation of concrete specimens and the results agreed with experiments well. This provides us with possibility to study the nonlinearity of concrete structures from a new perspective. However, as far as high arch dams are concerned, it's far from realistic to model exactly all components of concrete on the mesoscopic level in the seismic analysis. So some compromises become inevitable. Most important of all, an arch dam is discretized with finite elements, matrices, aggregate and interfaces may coexist in one element. Then this finite element model is viewed as a sample space. If there're plenty of samples in this space, in other words, the dam is discretized with plenty of finite elements, the material properties of elements can be assumed to conform to some specific distribution, such as Weibull distribution. In this way, the heterogeneity of concrete on the mesoscopic level can be reflected to some degree. Certainly the most important thing is that enough elements are employed to model to dam.

So here comes another question. The seismic analysis of an arch dam discretized with plenty of elements surely requires great computational effort, and this could be beyond the capacity of conventional personal computers. Besides, a comprehensive numerical program for aseismic analysis of arch dams needs to take into consideration many aspects, such as dam-foundation interaction, contraction joints, nonlinearity of the foundation, stability of the abutments and so on. Actually, it is the trend to model as much aspects as possible in aseismic evaluation of high arch dams. Such comprehensive analysis is also associated with substantive computations. No matter how fast PC techniques develop, PCs can not meet the needs for large-scale analysis in the long run. On the contrary, by employing parallel computing, the codes can be executed hundreds or thousands of times faster than in serial, the models constructed can then be far more accurate, incorporating more comprehensive representations of the physical and mechanical processes involved, and also allowing for greater resolution in the computational domain. In a word, parallel computing should be the ultimate solution for massive computing.

Aiming at the damage process simulation of arch dams, a parallel program PDPAD was developed using the above-mentioned damage simulation model for seismic analysis of arch dams and executed on a 4-node PC cluster platform. A 210m high dam was employed as verification and the result accords with shaking table test, which proves the validity and efficiency of the damage model and parallel program.

2. DAMAGE PREIDCTION MODEL OF ARCH DAMS INCORPORATING MESOSCOPIC

HETERGENEITY

2.1. Incorporation of heterogeneity

As mentioned in the above section, concrete is heterogeneous on the mesoscopic level. It has been found that the deformation and fracture of concrete is associated with very complicated progressive failures, as characterized by initiation, propagation, and coalescence of microcracks due to material heterogeneity. Although it's impossible yet unnecessary to precisely define the heterogeneity of all components in the seismic analysis of arch dams, it's suitable to assume that elements conform to a certain random distribution law when the dam is modeled with plenty of finite elements. Here the size of element is chosen according to the following rules. On one hand, it should be fine enough so that the mesoscopic heterogeneity causes difference in the properties of elements. On the other hand, it should be coarse enough so that every element can be idealized as homogeneous in itself.

Weibull distribution is chosen to represent the mesoscopic heterogeneity of concrete according to Tang's experience. The probability dense function of Weibull distribution is,

$$f(x)=\frac{\alpha}{\beta}\left(\frac{x}{\beta}\right)^{\alpha-1}\exp\left[-\left(\frac{x}{\beta}\right)^{\alpha}\right],\quad x\geq 0 \tag{2.1}$$

Here x could be the elastic modulus, strength, poisson ratio and mass density, indicating that these properties conform to Weibull distribution. β is average value of these mechanical properties and α is defined as the homogeneity index of concrete. A greater α implies that more elements are allocated with mechanical properties close to the mean value, thus the dam concrete is more homogeneous.

2.2. Elastic damage model

Concrete is a kind of quasi-brittle material, the nonlinearity in its deformation and cracking process is closely related to the initiation and propagation of micro-cracks, indicating the gradual deterioration of concrete. In conventional analysis of concrete, complicated models exhibiting nonlinearity and plasticity are employed to characterize the behavior of concrete, which requires complex programming and determination of relevant parameters. In order to reflect the basic qualities of concrete as far as possible, and in the meantime simplify numerical simulation, the constitutive of each small element is assumed to be elasto-brittle at failure. This can be verified by the acoustic emission observed in the cracking process of concrete since acoustic emission happens only in elastic failure.

Elastic damage model is employed to represent the behavior of concrete. The elastic modulus of every element follows the initial value until its stress state meets the failure criterion, then the modulus is updated as damage progresses,

$$\sigma=E\varepsilon=E_0(1-D)\varepsilon \tag{2.2}$$

Here E_0 and E represent the initial undamaged elastic modulus and updated modulus of damaged element respectively, D is the damage variable. D=0 corresponds to undamaged state while D=1 implies a totally damage element.

At the beginning, a linear relationship between stress and strain exists until the tensile stress exceeds its tensile strength f_t, when damage occurs and is quantified according to the maximum tensile strain ε_t. The development of microcracks causes a continual linear decrease of its tensile strength from a peak value f_t to residual strength f_{tr}, together with an increase in deformation. This reflects the strain softening observed in concrete. At the end of the strain softening regime, strain ε_{tr} is reached and then the element can sustain only low tensile strength, namely residual strength f_{tr}. Here f_{tr} is assumed to be a fraction of the tensile strength f_t. In this period, damage is already serious but the crack keeps on growing until the ultimate tensile strain ε_{tu} is exceeded, which means the element is totally damaged with *D*=1. For sake of numerical stability and simplicity, the elastic modus is assumed a sufficiently low value rather than the element being removed. Since this is an elastic damage model, the stress-strain curve returns to the origin at unloading, with no plastic strain considered. The stress-strain curve of concrete under uniaxial tensile loading is depicted in Fig.1 and the damage evolution law is defined according to the maximum tensile strain ε_t as follows.

$$D_t = \begin{cases} 0 & \varepsilon_t < \varepsilon_{t0} \\ 1-(\dfrac{\lambda-1}{\eta-1}+\dfrac{\eta-\lambda}{\eta-1}\dfrac{\varepsilon_{t0}}{\varepsilon_t}) & \varepsilon_{t0} \le \varepsilon_t < \varepsilon_{tr} \\ 1-\dfrac{\lambda\varepsilon_{t0}}{\varepsilon_t} & \varepsilon_{tr} \le \varepsilon_t < \varepsilon_{tu} \\ 1 & \varepsilon_t \ge \varepsilon_{tu} \end{cases} \tag{2.3}$$

where ε_{t0} is the elastic strain, λ is a coefficient ranging from 0 to 1 defined by $\lambda = f_{tr}/f_t$, η characterizes the strain softening regime with a value greater than or equal to 1, $\eta = \varepsilon_{tr}/\varepsilon_{t0}$. When $\lambda = 0$ and $\eta = 1$ are assumed, the damage evolution degenerates to elastic-brittle form, exhibiting neither strain softening nor residual strength. ξ defines the ultimate strain, $\xi = \varepsilon_{tu}/\varepsilon_{t0}$ 。

It's to be noted that the post-peak regime of the stress-strain curve needs to be modified to ensure mesh objectivity as shown in Fig.2. The fracture energy per unit area G_f is defined as

$$G_f = l_{ch} g_t \tag{2.4}$$

where g_t is the upper bound of total available energy of the material (total area under stress-strain curve), l_{ch} is the characteristic length defined by the cube root the volume of the element.

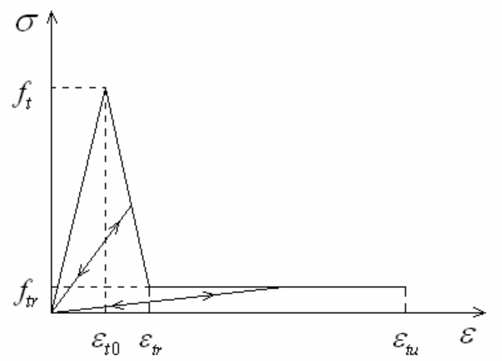


Fig.1 Damage evolution law for element under tensile loading

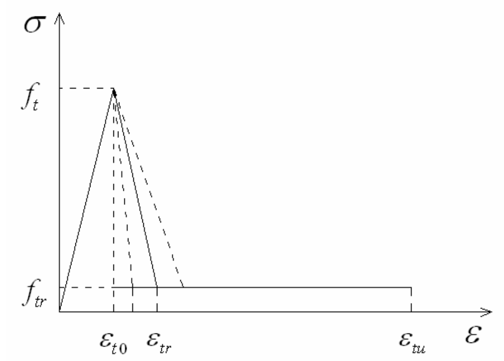


Fig.2 Modification of stress-strain curve concrete to ensure mesh objectivity

Aside from tensile damage, shear damage is considered. Mohr-Coulomb criterion is employed as the threshold. Once the stress state meets the Mohr-Coulomb criterion, the shear damage is evaluated according to the compressive strain.

$$D_c = \left\{ \begin{matrix} 0 & \varepsilon_c > \varepsilon_{c0} \\ 1-(\varepsilon_{c0}/\varepsilon_c)^N & \varepsilon_{c0} \ge \varepsilon_c > \varepsilon_{cu} \\ 1 & \varepsilon_c \le \varepsilon_{cu} \end{matrix} \right\} \tag{2.5}$$

where f_c is the uniaxial compressive strength of the element, ε_{c0} and ε_{cu} denote the elastic strain and ultimate strain under uniaxial compressive strength respectively. ς is defined as the ultimate strain coefficient, $\varsigma = \varepsilon_{cu}/\varepsilon_{c0}$ and ς=100 is assumed in this paper。 ε_c is the compressive strain under uniaxial compressive loading, ε_c is replaced in multiaxial cases by equivalent strain $\bar{\varepsilon} = \sqrt{\langle -\varepsilon_1 \rangle^2 + \langle -\varepsilon_2 \rangle^2 + \langle -\varepsilon_3 \rangle^2}$ 。N is a parameter for the exponential curve。

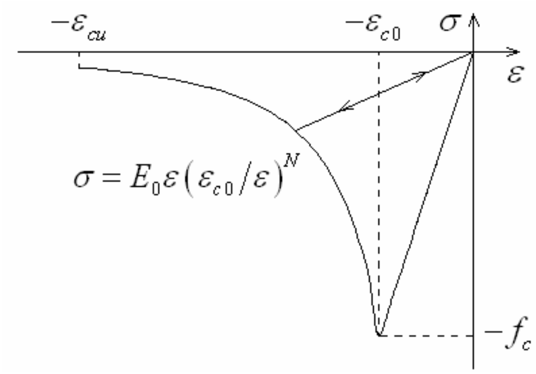


Fig.3 Damage evolution law for concrete element under uniaxial compressive loading

Since the compressive strength of concrete is much higher than its tensile strength, and arch dams in earthquakes tends to suffer damage caused by its tensile strength, the determination of tensile damage has priority over the determination of shear damage.

Totally damaged elements are hided in the image output to create crack profiles, but actually they're not removed from the topology, such that no remeshing techniques are required and computational effort can be greatly saved without loss of accuracy. What's more, the presented procedure also serves as an attempt to simulate the conversion of medium from continua to non-continua in a unified model.

3. PAPALLEL PROGRAM FOR DAMAGE PREDICTION OF ARCH DAMS IN EARTHQUAKES

Nonlinear analysis of high arch dams consists of a large number of finite elements exposes great challenge to our computational capacity, running such a simulation for tens of thousand of time steps can be extremely computationally intensive. Powerful parallel computing is the natural candidate.

Based on a finite element generator named PFEPG, a parallel program PDPAD (Parallel program for the Damage Prediction of Arch Dams) was developed with the damage model presented for the damage prediction of arch dams in earthquakes. An efficient parallel program has two requirement: (1)the number of DOFs(degree of freedom) per processor must be balanced, and (2) the spatial region owned by a processor must be geometrically compact to enable neighbors to be found quickly and with a minimum of communication. In PDPAD, domain decomposition method with overlapping was employed. Fig.4 shows the decomposition of dam-foundation system into six subdomains.

PDPAD was designed to run on a cluster with distributed memory structure, and programming model SIMD (single-instruction multi-data) was employed. Although the same codes are run on different processors, the processes fall into two categories: one master process and the others are slave processes. They're defined by their unique rank number and they execute different instructions controlled by a switch. Master process is a control process, doing jobs such as domain decomposition, task allocation to slave processes, iteration estimation, data gathering & distribution, I/O and so on. Every slave process is allocated with a certain domain of the finite element model and is responsible for the analysis of this domain. Communication only takes place between master process and slave processes, and no communication between slave processes is allowed. The communication is realized by MPI (Message Passing Interface).

For the case of dynamic loading, arch dam under static load is assumed as an initial state. It means that damage may have existed before the earthquake.

4. NUMERICAL EXAMPLE

PDPAD has been used to analyses the 210m high Dagangshan arch dam subjected to seismic loading. The dam is under construction now, with design acceleration of 0.5575g, which is the highest in the arch dam design history in China. The geometry and finite discretization of the dam is shown in Fig.4. Different colors of subdomains imply the result of domain decomposition and 6 subdomains in all are used in the paper. It's to be mentioned that a shaking table test of the model of the dam was carried out for comparison with numerical simulation, so in order to simulate the case in the test, a small foundation domain is simulated adjacent to the dam as in Fig.4.
The material properties of every element in the dam were randomly allocated through the Weibull distribution. The average material properties for the dam are: E=24GPa, ν=0.17, ρ=2641.65 kg/m^3, f_c=30MPa, f_t=3MPa. These values correspond to β in the Weibull distribution, the inhomogneity coefficient α=6 for E, f_c and f_t, and α=100 for ν and ρ are assumed. The strength and modulus are increased by 30% for dynamic loading. Since no damage was observed concerning the foundation in the test, the foundation is assumed to be homogeneous with the same elastic parameters (E, ν, ρ) as the dam and no damage was considered.
The model has been discretized with eight node isoparametric brick elements. The size of element in the dam is less than 3m and in the foundation less than 18m. The dam-foundation system was discretized with 358956 elements and 386276 nodes, over one million DOFs (Degrees Of Freedom) were involved.

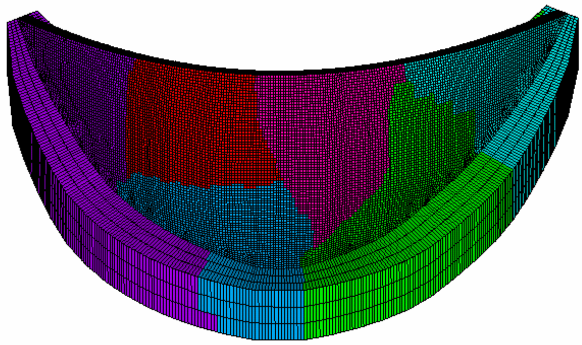
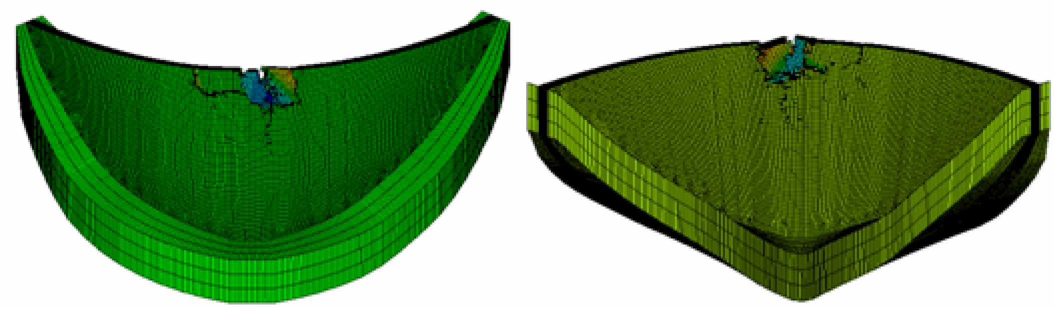


Fig.4 Finite element discretization and domain decomposition of dam-foundation system (6 subdomains)

Rayleigh damping has been used and the damping ratio for all modes of vibration is 5%. An empty reservoir was considered and artificial ground motion with amplitude of 1.0g was introduced in the upstream-downstream direction.
The static load refers to the self-weight of the dam-foundation system in this case. Compressive stress was dominant, only a few elements were damaged owing to their low tensile strength and these elements were randomly distributed. At the beginning of the ground motion, damage were still randomly scattered over the dam. Then as the ground motion intensifies, the tensile strain at the top of the central cantilever increased quickly. Elements were damaged one by one in this area (localized damage) and the first crack appeared. Then the crack propagated downward by 1/5 of the dam height, leading to the release of tensile stress at the arch direction, which in turn caused an excessive tensile strain in the beam direction. Soon the crack propagated horizontally to the left and right in the meantime. The horizontal cracks met new vertical cracks near the central top, causing concrete blocks to lose support from the dam.
The ultimate damage of the dam is shown in Fig.5. Cracks are localized at the vicinity of central top of the dam, no visible crack was detected elsewhere. Besides, statistics show that vast majority of damage is caused by excessive tensile strength.
The arch dam model after the shaking table test is shown in Fig.6. It could be seen that the damage modes obtained by numerical simulation and model test are very similar, which verifies the validity of the proposed damage model and the parallel program PDPAD.



upstream side downstream side

Fig.5 Damage of the arch dam (numerical prediction by PDPAD)

upstream side downstream side

Fig.6 Damage of the arch dam (shaking table model test)

5. CONCLUSION

Aiming at the damage process of high arch dams in strong earthquakes, a damage model with the inheterogeneity of concrete on the mesoscopic level considered was presented. By discretizing the dam with plenty of small elements and using Weibull distribution to characterize the inheterogeneity of material properties, the behavior of elements is modeled with elastic damage model and Mohr-Coulomb Principle with tension cut-off. Using this model, a special parallel program PDPAD was developed.

The parallel program PDPAD was employed in the seismic analysis of Dagangshan arch dam. Numerical result accords with results of shaking table test, which verifies the validity of the presented model. Several conclusions can be made:

1) Inhomogeneity of concrete on the mesoscopic level is important to the damage analysis of arch dams, some new insights might be obtained concerning the damage mechanism of dams.
2) The nonlinearity of concrete is closely associated with its inhomogeneity, by employing elastic damage model and simple failure criterion can characterize complex nonlinearity such as crack initiation and propagation.
3) Parallel computing is a powerful tool for large-scale computation. It enables more accurate and comprehensive simulation of high arch dams in earthquakes.
4) The vicinity of the top of the central cantilever is a weak part of arch dams in earthquakes. Cracks tend to initiate and propagate in this region.
5) The crack of dam concrete is caused mainly by excessive tensile strength.

6. ACKNOWLEDGEMENT

This research has been supported by National Nature Science Foundation of China under Grant No. 90510018, for which the authors are grateful. Besides, the authors wish to thank: 1.Prof. C. A. Tang and Dr. Z. Z. Liang for their suggestions on the damage model, 2. Prof. J. Y. Chen for carrying out the model test of arch dam, 3. G. P.

Liang and Dr. S. P. Liu for support on the development of the parallel program PDPAD.

REFERENCES

[1] Valliappan, S., Yazdchi, M., and Khalili, N. (1996). Earthquake analysis of gravity dams based on damage mechanics concept. *International Journal for Numerical Methods in Geomechanics* **20**, 725-751.

[2] Ghrib, F. and Tinawi, R. (1995). An application of damage mechanics for seismic analysis of concrete gravity dams. *Earthquake Engineering and Structural Dynamics* **24**, 157-173.

[3] Lee, J. and Fenves, G. L. (1998). A plastic−damage concrete model for earthquake analysis of dams. *Earthquake Engineering and Structural Dynamics* **4**, 937-956.

[4] Valliappan, S., Yazdchi, M. and Khalili, N. (1999). Seismic analysis of arch dam—a continuum damage mechanics approach. *International Journal of Numerical Methods Engineering* **45**, 1695-1724.

[5] Lotfi, V. and Espandar, R. (2004). Seismic analysis of concrete arch dams by combined discrete crack and non-orthogonal smeared crack technique. *Engineering Structures* **26**, 27-37.

[6] Chen, J., Li, J. and Lin, G. (2003). Seismic response analysis of high arch dam based on strain rate-dependent concrete damage model. *China Civil Engineering Journal* **36:10**, 46-50. (in Chinese).

[7] Cui, Y., Zhang, C. and Xu, Y. et al. (2002). Failure simulation of the Meihua arch dam. *Journal of Tsinghua University(Science and Technology)* **42:S1**, 88-92. (in Chinese).

[8] Pan, J., Long, Y. and Zhang, C. (2007). Seismic cracking of arch dams and effectiveness of strengthening by reinforcement. *Journal of Hydraulic Engineering* **38:8**, 926-932. (in Chinese).

[9] Tang, C., and Zhu, W. (2002). Concrete Damage and Failure-Numerical Test, Science Press, Beijing, China. (in Chinese).