# NONLINEAR SEISMIC ANALYSIS OF ARCH DAMS WITH CONTRACTION JOINTS AND DAM-WATER-FOUNDATION INTERACTION

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**ABSTRACT :**

A new algorithm—Mixed Finite Element Method, was proposed for nonlinear dynamic fictional contact problems of high arch dams with contraction joints. Based on this method, the system of forces acting on the contactor was divided into two parts: external forces and contact forces. The displacements of contactor were chosen as the basic variables and the nodal contact forces on possible contact region were chosen as the iterate variables, so that the nonlinear iteration process was only limited on the possible contact surface. In this way, the sophisticated contact nonlinearity was shown by the variety of the contact forces. Thus the iterative procedure became easily to be carried out and much more economical. The numerical method for the analysis of dynamic dam-water-interaction, integrated solution base on the generalized Newmark-β direct integral method, was discussed to establish a method which is fairly simplified but without loss of accuracy for the simulation of the dynamic pressure of the water. The artificial multi-transmitting boundary condition with implicit finite element algorithm is applied to the nonlinear seismic analysis of high arch dams together with the mixed finite element method for fictional contact problems and the algorithm for dam-water-interaction. In this way, a fairly perfect and high efficiency analysis method for seismic analysis of arch dams with contraction joints and dam-water-foundation interaction. Some valuable conclusions were obtained from the calculation and analysis of the seismic response of a high arch dam following the proposed method.

**KEYWORDS:** fictional contact problem, dam-water-foundation interaction, artificial boundary condition, nonlinear seismic response

## 1. INTRODUCTION

For construction facilitation and in order to control tensile forces due to concrete shrinkage, temperature variations, concrete arch dams are typically built in cantilever monoliths separated by vertical contraction joints. Opening and closing or sliding of the contraction joints will happen during earthquakes in reality， Several studies [Gregory L. Fenves and Soheil Mojtahedi,1993],[B. Weber, J-M. Hohberg and H. Bachmann,1990], [Ahmadi MT and Razavi S,1992] show that the contraction joint plays an important role in the nonlinear response of high arch dams during strong earthquakes.

The importance of the joint-opening mechanism has motivated several analytical research efforts. The joint behavior in arch dams was described by Clough [Fenves G L, Mojtahedi S and Reimer R B,1992]. Dowling and Hall [Dowling M L and Hall J F,1989] have presented a discrete joint model represented by nonlinear springs for arch dams that takes into account the gradual opening and closing of vertical contraction joints and horizontal cold joints. Fenves et al. [Fenves G L, Mojtahedi S and Reimer R B,1992] developed a nonlinear joint element and numerical analysis procedure for calculating of the nonlinear seismic response of arch dams when the contraction joints open and close. In fact, the behavior of contraction joints on the response of the arch dams can be regard as typical dynamic contact problems with friction and initial gaps. Problems involving contact with friction and initial gaps are among the most challenging ones in solid mechanics and at the same time of crucial practical importance in many engineering branches. The chief difficulty in simulating those problems lies in their inherent and strong nonlinearity, which comes from that both the region of contact and the contact forces distribution are unknown prior to the analysis. Although several formulation procedures have

been developed for contact problems, there is still a great need for a reliable, accurate, especially more effective method.

Other two key factors for the seismic analysis of arch dams are the dam-water-interaction and the effects of radiation damping of infinite foundation. A new integrated solution base on the generalized Newmark-β direct integral method [M.G.KATONA, ZIENKIEWICZ,1985] was established for the dynamic analysis of dam-water interaction. The artificial multi-transmitting boundary condition with implicit finite element algorithm is applied to the nonlinear seismic analysis of high arch dams together with the mixed finite element method for fictional contact problems and the algorithm for dam-water-interaction. The purpose of the paper is to provide a numerical method to simulate the nonlinear seismic response of the arch dams with the consideration of the above three important factors.

## 2. DYNAMIC CONTACT MODEL

### *2.1 mechanical descriptions*

With no loss of generality, consider two elastic bodies $\Omega_1$ 、 $\Omega_2$, as shown in Figure 1, which are brought into contact by the external force $F$ . Each boundary of the two bodies $\Gamma^I$ is divided into three disjoint parts $\Gamma^I = \Gamma_t^I + \Gamma_u^I + \Gamma_c^I$ : $\Gamma_c^I$ which is the potential contact region. Here the superscript $I = 1,2$ denotes the two bodies, respectively. Other notations used in this section are given as follow: $f^I$: contact forces on $\Gamma_c^I$; $f_\xi, f_\eta, f_\zeta$ : component of contact forces $f$ in local coordinate $\xi\eta\zeta$ , respectively; $u^I$ : displacement vector on $\Gamma_c^I$; $\delta$ is the gaps between $\Omega_1$ and $\Omega_2$ measured in the normal direction, $\delta = (u^1 - u^2)\cdot\vec{\xi} + \delta_0$, where $\vec{\xi}$ is the normal direction to the contact region, $\delta_0$ is the initial normal gaps.

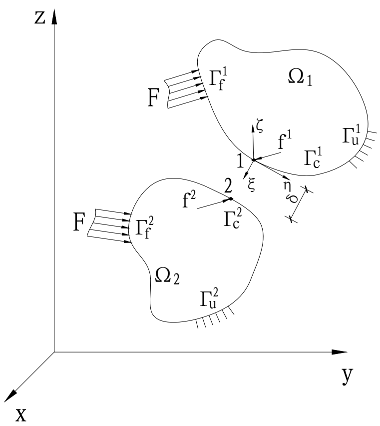


Figure 1: Mechanical model for contact problems

For contact problems, three important principles, the impenetration condition, normal traction condition and frictional condition, must be taken into account. When the three contact statuses (stick, slip and separation) are involved, those conditions mentioned above can be summarized as Table 1:

Table 1: Contact conditions for contact problems with friction and initial gaps

| Contact status | Equality constraint | Inequality constraint |
|---|---|---|
| Separation | $f^1 = f^2 = 0$ | $\delta > 0$ |
| Stick | $\delta = 0, f^1 = -f^2$ | $f_\xi < \sigma_t \cdot A, \sqrt{f_\eta^2 + f_\zeta^2} < -\mu \cdot f_\xi + A \cdot c$ |
| Slip | $\delta = 0, \sqrt{f_\eta^2 + f_\zeta^2} = -\mu \cdot f_\xi + A \cdot c$ | $f_\xi < \sigma_t \cdot A$ |

### *2.2 Finite Element Formulations*

Assuming that the analysis of $n^{th}$ step has been finished, the incremental dynamic equilibrium equation for $n+1^{th}$ step at time can be expressed as:

$$M\ddot{u}_{n+1} + D\dot{u}_{n+1} + Ku_{n+1} = F_{n+1} + f_n + \Delta f_n \tag{2.1}$$

where $M$ is the global mass matrix; $D$ is the global damping matrix, here the proportional Rayleigh damping assumption is adopted $D = \alpha M + \beta K$; $K$ is the global stiffness matrix; $F_{n+1}$ is the vector of total external load at time t+Δt; $f_n$ is the vector of total contact force at time t; and $\Delta f_n$, vector of incremental contact force at time t which are greatly concerned about. $u_{n+1}$, $\dot{u}_{n+1}$, $\ddot{u}_{n+1}$ is the vector of displacement increment, velocity increment, acceleration increment at time t+Δt, respectively, the superscript ( • ) refers to time differential.

Following the generalized Newmark time integration scheme, the equation with the variables of the acceleration increment is obtained as:

$$\overline{K}\Delta\ddot{u}_n = \Delta\overline{F}_n + \Delta f_n \tag{2.2}$$

where $\overline{K}$, $\Delta\overline{F}_n$ is the effective stiffness matrix and effective external load increment and can be expressed as following, respectively:

$$\overline{K} = (1.0 + \alpha\beta_1\Delta t)M + (\beta\beta_1\Delta t + \beta_2\Delta t^2)K \tag{2.3}$$

$$\Delta\overline{F}_n = F_{n+1} + f_n - (\ddot{u}_n + \alpha\dot{u}_n^p)M - (u_n^p + \beta\dot{u}_n^p)K \tag{2.4}$$

Here the superscript $p$ refers to the predicted quantities, $\beta_1$, $\beta_2$ are Newmark parameters for time integration. Introducing the matrix $C$ into above equation, equation (2.2) can be rewritten as

$$\Delta\ddot{u}_n = \overline{K}^{-1}\Delta\overline{F}_n + C\Delta f_n \tag{2.5}$$

where the matrix $C$ is the flexibility matrix which is defined on the possible contact boundary $\Gamma_c^I$. An arbitrary component of $C$, $c_{ij}$, represents flexibility coefficient corresponding to the acceleration at the freedom $i$ due to a unit force at the freedom $j$.

Considering equation (2.5) and $\Delta u_n = u_{n+1} - u_n$, if $\Delta\overline{u}_n$ is defined as

$$\Delta\overline{u}_n = u_n^p + \beta_2\Delta t^2\overline{K}^{-1}\Delta\overline{F}_n - u_n \tag{2.6}$$

one obtains

$$\Delta u_n = \Delta \bar{u}_n + \beta_2 \Delta t^2 C \Delta f_n \tag{2.7}$$

It is important to be noted out that equation (2.5), equation (2.7), and the following equations in this section are only performed for the DOF (Degree of Freedom) on the possible contact surface, not for all the DOF of the whole system.

According to the Newton's third law, it is obvious that $\Delta f_n^1 = -\Delta f_n^2 = \Delta f_n$, and moreover, incorporating flexibility matrix $C^1$ and $C^2$ into $C = C^1 + C^2$, applying above equation (2.7) to point 1 and 2 of a given node pair, it gives

$$C\Delta f_n = \frac{1}{\beta_2 \Delta t^2}((\Delta u_n^1 - \Delta u_n^2) - (\Delta \bar{u}_n^1 - \Delta \bar{u}_n^2)) \tag{2.8}$$

Equation (2.8) is the finite element compliance equation of the mixed finite element method for the dynamic contact problems proposed in this paper. In this equation, the second term in right-hand-side, $(\Delta \bar{u}_n^1 - \Delta \bar{u}_n^2)$, stands for the difference of incremental displacement only due to the external load increment, as can be seen easily from equation (2.6). Therefore, it is nothing to do with the current contact status and can be obtained by back-substitution directly. While as for the first term in right-hand-side, $(\Delta u_n^1 - \Delta u_n^2)$ it denotes the difference of incremental displacement induced by both the external load increment and the contact force increment. From this view of point, both the right-hand-side and the left-hand-side of the above equation are associated with the contact state. An iterative method taking into account different contact status is necessary to solve the equation.

## 3. NUMERICAL SCHEME FOR DAM- RESERVOIR DYNAMIC INTERACTION

Considering free surface boundary, fluid-structure-interaction boundary, fluid absorb boundary and bottom absorb boundary, the governing equation of the fluid domain can be discretized by the standard Galerkin weighted residual method [ZHAO, 2006]. Combining with the general dynamic equilibrium equation for the solid domain, the finite element formulations for the dynamic dam-water interaction can be expressed as following:

$$\begin{cases} M\ddot{u} + D\dot{u} + Ku - \dfrac{1}{\rho} S^T P + F_e = 0 \\ G\ddot{P} + H\dot{P} + QP + S\ddot{u} + S\ddot{u}_g = 0 \end{cases} \tag{3.1}$$

where $G = \frac{1}{g}\int N_f^T N_f d\Gamma_1 + \frac{1}{c^2}\int N_f^T N_f d\Omega$, $H = \frac{1}{c}\int N_f^T N_f d\Gamma_3 + A\int N_f^T N_f d\Gamma_4$,
$Q = \int \nabla N_f^T \nabla N_f d\Omega$, $S = \rho \int N_f^T L N_s d\Gamma_2$.

Following the generalized Newmark time integration scheme, the above equation can be rewritten in time domain as following which can be solved step by step

$$\begin{bmatrix} (1.0 + \alpha\beta_1 \Delta t)M + (\beta\beta_1 \Delta t + \beta_2 \Delta t^2)K & \Phi S^T \\ \Phi S & \Phi(G + \beta_1 \Delta t H + \beta_2 \Delta t^2 Q) \end{bmatrix} \begin{Bmatrix} \Delta \ddot{u}_n \\ \Delta \ddot{P}_n \end{Bmatrix} = \begin{Bmatrix} R_{u,n+1} \\ \Phi R_{p,n+1} \end{Bmatrix} \tag{3.2}$$

Where $R_{u,n+1}$ and $R_{p,n+1}$ represents the generalized load vector for the solid domain and fluid domain, while $\Phi$ is a coefficient with value of $-\frac{1}{\rho}\beta_2 \Delta t^2$ for matrix symmetric consideration.

## 4. SIMULATION OF THE RADIATION DAMPING EFFECT

In the seismic analysis of high concrete dams in hydraulic engineering, the traditional model of fixed boundary with massless foundation were often adapted, and the radiation damping of foundation and the inhomogeneity input of wave-motion could not be taken into account. In order to overcome the defect of traditional methods and to find a new simple and effective time-domain method to eliminate the influence of boundary reflection, the two order multi-transmitting formula (MTF) given by LIAO[LIAO, H L WONG, B YANG and Y YUAN,1984] was employed in this paper. Following the artificial boundary condition (ABC) based on MTF, the foundation of the structure was divided into two parts: inner region and outer region. The inner region is solved by implicit finite element formulation mentioned above, while the outer region is solved by MTF explicitly. In this way, the artificial multi-transmitting boundary condition was combined with implicit finite element formulation and applied to the nonlinear seismic analysis of high arch dams together with the mixed finite element method for fictional contact problems and the algorithm for dam-water interaction

## 5. APPLICATION

The previously developed model has been applied to the seismic response of a high arch dam with contraction joints. The material properties are: modulus of elasticity E=22*Gpa*, Poisson's ratio $\nu = 0.167$, coefficient of friction $\mu = 0.7$, unit weight $\rho = 24.0kN/m^3$, cohesive strength $c = 0$, initial tensile strength $\sigma_t = 0.5MPa$, initial normal gaps $\delta_0 = 0$. The dam is a 235-*m* high double-curvature arch dam. It has a crest length of 304.8*m*, and the thickness of the center cantilever varies from 48*m* at the base to 10*m* at the crest. The dam consists of fourteen cantilevers separated by thirteen contraction joints. Finite element model of the dam and the layout of transverse joints are shown in Figure 2. An artificial ground motion, is applied both in the stream and cross-stream direction. The opening and closing of the joints and its effects to the response of dam under the excitation of ground motion are studied. Solution for the static response of the dam-water-foundation with upstream water level 202*m* is obtained before determining the nonlinear earthquake response.

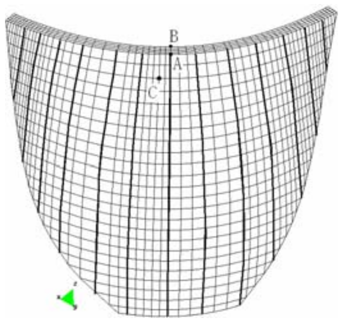


Figure. 2. Finite element model and layout of transverse joints

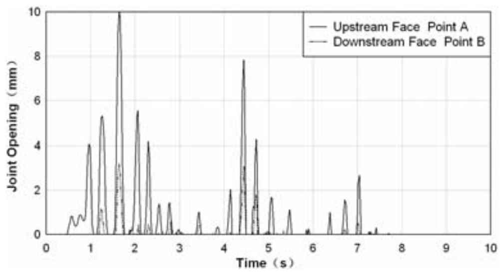


Figure. 3. Time histories of joint opening

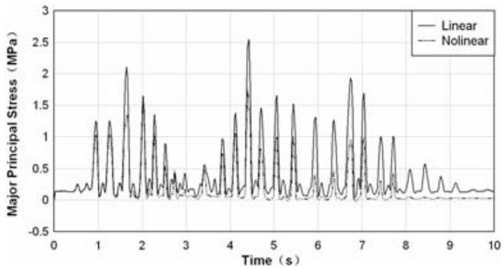


Figure. 4. Time histories of major principal stress

Time histories of joint openings of point A and B, as marked in Figure 2, are plotted in Figure 3, while Figure 4 gives the time histories of the major principal stress of point c, both in the case of contraction joints are considered or not.

It is founded that once the tensile stress exceeds the tensile strength during the earthquake, the joints will open and consequently the tensile stress will be released. This is because large arch tensile stresses can not be transferred across the contraction joints, hence arch tensile stresses releasing and the internal forces redistributing from the arch action to cantilever action will take place. Some researchers have drawn the same conclusion about this, as in [Lotfi V, Espandar R,2002],[ Ahmadi M T,Izadinia M and Bachmann H,2001].

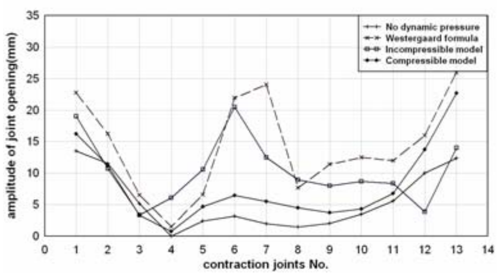


Figure 5 Comparison of joint opening by different reservoir models

The joint opening is an important calculating index for the seismic analysis of arch dams with contraction joints. The effects of different reservoir models on joint opening of high arch dams are shown in Figure 5. The results show that remarkable calculation error would induce if the water compressibility is omitted. Both the amplitude and the distribution of the maximal joint opening along the dam axis are different compare with the compressible case. The Westergaard formulation [R W CLOUGH,1982] and the incompressible model exaggerate the effect of the water, and the compressible model is recommended for the dynamic characteristic analysis of high arch dams.

## 6. CONCLUSION

A new effective iterative method—Mixed Finite Element Method for the solution of dynamic contact problems is presented. Firstly, the mechanical model for three-dimensional dynamic frictional contact problems with initial gaps is presented, and then the finite element compliance equation is derived. The iteration process is given in detail at last. The proposed method is applied to the seismic response of high arch dams with contraction joints. It compares well to results obtained by others.

It is to be noted out that, for a structure with several joints, for instance arch dams, the system is divided into several substructures by joints. The substructure keeps its linearity during loading if the material is linear elastic one. Some methods couple all the DOF of the joints together according to the condensation of DOF, thus the flexible matrix obtained through those methods is a full matrix, which is not easy to handle. However, numerical studies have shown that it is only necessary to retain the coupling between two adjacent joints. In effect, each linear substructure is only coupled to its adjacent substructures through foundation. From this point of view, the flexibility matrix obtained in this paper is symmetric and sparse, thus the iterative procedure become easier to be carried out and much more economical.

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