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Safety Analysis of Arch Dam with Strength Reverse Method

Xiao-lian Zhao [1,a], Yu Xia [2, b], Da-wei Wang [3,c] and Zhong-qing Zhang [4,d]

[1] College of Resources and Environment, Guangxi University, Nanning China

[2]Civil Engineering and Architecture Department of Guangxi University of technology, Liuzhou, China

[3]Guangxi Communications Planning Surveying and Designing Institute, Nanning China

[4]College of Civil and Architecture Engineering, Guangxi University, Nanning, China

[a]xiaolianbsh@126.com, [b]summ-rain@163.com, [c]76640410@qq.com, [d]zhangzq@gxu.edu.cn

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Abstract: Arch dam's failure is a super nonlinear irreversible process. The research on process of it would give quite important information for safety evaluation. In this paper, it analyses overload of the highest RCC arch dam of the world by strength reverse method and shows the process of dam's failure from normal operation, local deformation to overall failure.

Introduction

Arch dam is a highly constrained structure, the failure process of it is gradually releasing redundant constraints and changing from a statically indeterminate structure to a statically determinate structure.. Paper [1] points out that we seldom consider dam's failure process when we are doing safety analysis, the theoretical basis are lacking. Paper [2] also points out that the study from microscopic damage to macro-instability of the failure process and mechanism of damage are the main development direction of future research. Paper [3] uses three-dimensional deformable discrete element method to simulate the dam's overall instability process, but location of cracks are pre-assumed. In this paper, it use explicit finite element method to simulate the failure process of overload.

Theory of Large Deformation [4]

The direct data method can be used for the elastic large deformation problem, which is known to directly solve structural deformation, strain and stress under loads and constraint. The configuration before deformation and the corresponding strain and stress are the unknown parameters, Kirchhoff stress and Green strain are generally used. The main iterative method is Newton method and quasi Newton method, etc. The problem relating historical deformation, such as viscoelastic material model and the time effect of inertia (dynamic problems), must use incremental method. It is discrete the variable of time ($t = 0, t_1, t_2, ...t_m, t_{m+1}, ...$), then gets the numerical solution of these discrete points. Solutions according to reference configuration can be divided into full Lagrangian format and updated Lagrangian format. The time interval between t and $t + \Delta t$, the reference configuration is that at the time of t in the former. Described stress and strain are mainly using Euler stress- σ_{ij} and the existing configuration of the infinitesimal strain; the reference is the configuration when $t_0 = 0$ in the later, the described strain and stress are mainly choosing S_{ij} of Kirchhoff stress and E_{ij} of initial described configuration. Two methods have almost the same efficiency. It mainly uses Updated Lagrange method in this paper. The control equations of the Updated Lagrangian are listed below.

conservation of mass

$$\rho(X,t)J(X,t) = \rho_0(X) \tag{1}$$

conservation of momentum

$$\frac{\partial \sigma_{ij}}{\partial x_j} + \rho b_i = \rho \ddot{u}_i \tag{2}$$

conservation of energy

$$\rho \dot{w}^{\text{int}} = D_{ji}\sigma_{ij} \tag{3}$$

deformation rate

$$D_{ij} = \frac{1}{2}\left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i}\right) \tag{4}$$

constitutive relation

$$\overset{\nabla}{\sigma} = \overset{\nabla}{\sigma}(D_{ij}, \sigma_{ij}, \cdots) \tag{5}$$

boundary condition

$$\begin{cases} (n_j \sigma_{ji})\big|_{A_t} = \overline{t}_i \\ v_i\big|_{A_v} = \overline{v}_i \end{cases} \tag{6}$$

initial conditions

$$\dot{u}(X,0) = \dot{u}_0(X) \quad \sigma(X,0) = \sigma(X)$$

or

$$\dot{u}(X,0) = \dot{u}_0(X) \quad \sigma(X,0) = \sigma(X) \tag{7}$$

Equation (3) requires to meet everywhere in the solution of the region, it is almost impossible to solve the equations directly. Numerical method only requires momentum equation to meet the requirement in the sense of inner product, According to the weak form of differential equations, we can get virtual power equation, which can get the node displacement equation when discrete. Take the virtual speed as weighting factor, using the weighted residual method, the weak form of momentum equation can be written as

$$\int_V \delta v_i \left(\frac{\partial \sigma_{ij}}{\partial x_j} + \rho b_i - \rho \ddot{u}_i\right) dV = 0 \tag{8}$$

where $\delta v_j(X) \in R_0 \quad R_0 = \left\{\delta v_j \middle| \delta v_j \in C^0(X), \delta v_j\big|_{A_v} = 0\right\}$ = virtual speed.

using distribution integral, equation (8) can be written as

$$\int_V \frac{\partial(\delta v_i)}{\partial x_j}\sigma_{ji} dV - \int_V \delta v_i \rho b_i dV - \int_{A_t} \delta v_i \overline{t} dA + \int_V \delta v_i \rho \ddot{u}_i dV = 0 \tag{9}$$

Equation (9) is virtual power equation. It is first to discrete structure space, which is the same with elastic finite element method to solve the same equation of virtual power, the space coordinates ($x_i(X,t)$) of particle X at any time is $x_i(X,t) = N_I x_{iI}(t)$ (10)

where N_I = the shape function of node I, repeated subscript indicates summation within their range. Thus it can get the displacement of any point X of element

$$u_i(X,t) = x_i(X,t) - X_i = N_I(X) u_{iI}(t) \tag{11}$$

where $u_{iI}(t) = x_{iI}(t) - X_{iI}$ = displacement of node I, similarly, speed, acceleration, deformation rate, and virtual speeds of any point within the unit can be expressed as

$$\begin{cases} \dot{u}_i(X,t) = N_I(X)\dot{u}_{iI}(t) \\ \dot{u}_i(X,t) = N_I(X)\ddot{u}_{iI}(t) \\ D_{ij} = \frac{1}{2}\left(\frac{\partial \dot{u}_i}{\partial x_j} + \frac{\partial \dot{u}_j}{\partial x_i}\right) = \frac{1}{2}\left(\dot{u}_{iI}\frac{\partial N_I}{\partial x_j} + \dot{u}_{jI}\frac{\partial N_I}{\partial x_i}\right) = B_I u_I \\ \delta v_i(x) = N_I(x)\delta v_{iI} \end{cases} \tag{12}$$

with all the equations above, the following equations can be got

$$M\ddot{U} + f^{\text{int}} = f^{ext} \tag{13}$$

where $f^{\text{int}} = \int_V B^T \sigma dV$, $f^{ext} = \int_V N^T \rho b dV + \int_{A_t} N\overline{t} dA$, $M = \int_V \rho N^T N dV + \int_{V_0} \rho_0 N^T N dV_0$ = mass matrix for the system. Independent of time, the computation is only needed at the initial time.

Calculation process

It uses three-dimensional 8-node hexahedron solid elements in the calculation. The element can choose between two algorithms: a single point of integration, full integration (2 × 2 × 2 points). The former is calculated quickly and effectively in the large deformation problem, hourglass control needed; the latter doesn't need hourglass control with low efficiency. For large Poisson's ratio, it will appear volume lock and shear lock. The results are relatively poor accuracy. The former is more sensitive to the shape of the element. Taking into account the complex of model, the large number of element, and special distortion of some elements, it chooses the first algorithm.

There are two methods to simulate crack formation and propagation. One is by the failure of elements, cracks appear in the structure when elements fail. The other is formed by defining node constraints, nodes lose their constraints, and then cracks are shown. The first method requires model elements must be small, or it will lead to large errors; it is very complicated to build model for the second method. In pre-treatment process of the finite element, the definition of constrain failure of the nodes is messy, it is impossible to be defined entirely by hand for the complex model. This article chooses the first method to simulate crack formation and expansion. In the loading process, the failure meeting any criteria set, will cause the material damage. Through elements destruction path, we can see cracks in structural and partial expansion of cracking. It can give a comparatively real failure process of arch dam.

All the loads of explicit analysis must be time-related. For this reason, an array of parameters is created to define load. In this calculation, the gravity, temperature and water load are imposed on arch dam. The overload water pressure on the dam is gradually increasing with time changing. It is shown in Table 1. The gravity load does not change in calculation. Temperature load is got in implicit calculation of finite element thermal analysis, then added temperature load into explicit compute.

When loads are imposed on model, in order to avoid impact of shock wave, it uses dynamic relaxation to eliminate their effects. It increases the damping and reduces the kinetic energy to zero, allowing an explicit solver for static analysis.

Finite element model

The direction of abutment is the x-axis, the direction of the right bank is x positive direction. The y-axis direction is along direction of the river, the downstream direction is y positive direction; z-axis direction is along the direction of dam height, the direction of dam height increasing is z-axis positive. Model includes 230 meters long, 510 meters wide, 420 meters high, the base of model is constrained by three directions, upstream and downstream boundary are constrained by constraints of y, left and right boundary are constrained by constraints of x, the model has a total of 157,032 elements, 179,436 nodes, It is shown in Fig. 1. The parameters used are shown in Table 2.

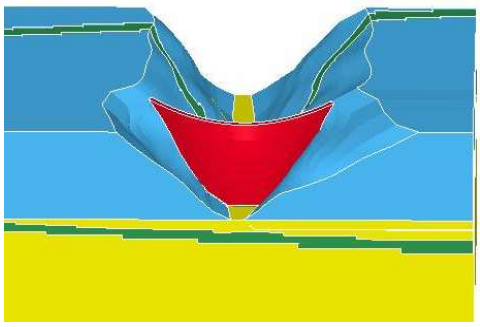

Fig. 1 Finite element model

Table 1 Load process of water pressure

Time (s)	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
Overload factor	1	2	3	4	5	6	7	8	9	10

Table 2 Material parameters

Location	Elastic modulus (Gpa)	Bulk density (KN/m^3)	Poisson's ratio	Cohesion(Mpa)	Friction angle (°)	Coefficient of thermal expansion(10^{-6})
Dam body	18	2350	0.167	2	56	4.87
Abutment	14	2730	0.25	0.9	45	
Base	11	0.27	0.27	0.7	42	
Unconformity	3	2660	0.3	0.35	35	

Conclusions

It gets failure process of arch dam with strength reverse method. The result is shown in Fig. 2. It is easy and intuitive to see the path of destruction and the crack propagation process.

Crack first begins from bottom of the dam. At first, there are several vertical cracks. Then the position of abutment appears crack and then there is horizontal crack in the height of two-thirds of arch dam. The horizontal cracks become total penetrating. The bottom arch ring of arch dam is gradually damaged. The most important cracks, which are affecting the safety of arch dam, appear when the overload factor is 2.5. So the overload coefficient of dam is about 2.5

The main reason is that the dam is strongly constrained by the abutment and base, with the load increasing, there is a larger tensile stress at the bottom of the dam. When crack appears, the stress is released. Then the high stress area moves to the upper location of the dam, leading to horizontal cracking and even penetrating cracks.

From the analysis, we also can find that the initial damage is usually at bottom and abutment of dam. The cracks are vertical at fist. With the load increasing, there are more and more cracks. When horizontal crack appearing, it will deeply affect the stability of the dam. Usually it indicates that the limited load is reaching. So when such cracks are found, they should be given special attention and research.

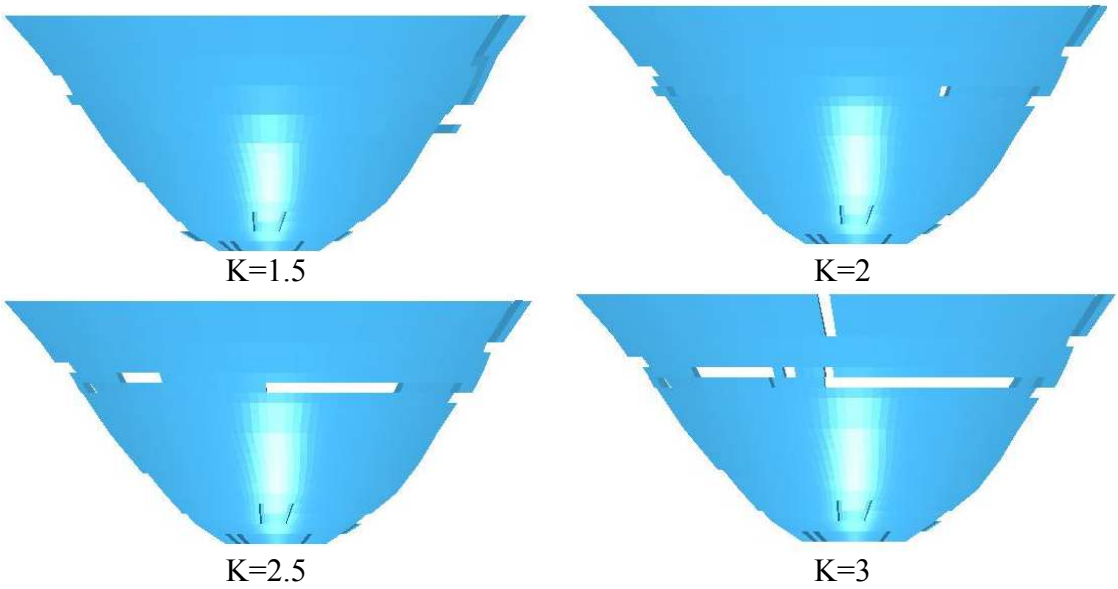

Fig. 2 Failure process by strength reverse method

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