Numerical Simulation of damage pattern of Earth Dams during the 2007 Ning'er Ms 6.4 Earthquake in Yunnan

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ABSTRACT: Based on the post-earthquake survey of the Ms 6.4 Ning'er earthquake, the 3D finite element method is used to simulate the earthquake response of the earth dam of Dahebian Reservoir. The displacement, stress and strain responses are calculated, and the results are reasonable while comparing with the cracks in the actual earthquake disasters.

KEYWORDS: earth dam, earthquake response, numerical simulation, finite element

1. INTRODUCTION

Among over 85,000 reservoirs built in China, 82,000 are small-scale that takes 96％, which play a key role in flood control, irrigation, water supply, power generation and ecosystem and environment protection (Sheng et al., 2006). However, due to various reasons (including design, construction and management and ageing of materials), the percentage of ill and sick reservoir is high. Besides all the problems mentioned above, the influence of earthquake on the water retaining structures of small scale reservoirs is another serious problem in seismic active regions, which can not be out of consideration (Zhu, et al., 2005). Hence, the stability of earth dam during earthquakes has been a major concern for the local people in Southwest China. It is an important topic to appraise the earth dam's hidden danger accurately and promptly, and to adopt the reinforcement measure. It also needed us to handle the conditions of the earth dam's stress and displacement. Based on the post-earthquake survey of the Ms 6.4 Ning'er Earthquake which happened in Yunnan Province, one of the high seismic hazard regions in China, on June 3, 2007, the seismic response analysis and the damage development simulation of the earth dam (belonging to one of the small scale reservoirs, named Dahebian Reservoir) are carried out.

2. BASIC ENGINEERING DATUM OF DAHEBIAN RESERVOIR

Dahebian Reservoir was completed and put into operation in December in 1996. It is located 10 kilometers northwest of Ning'er County Town (100°59′E, 23°06′N). So the reservoir plays an important role in protecting the people who lived in the lower reaches in Ning'er County (Fig. 1). The main dam of Dahebian Reservoir is a homogeneous earth dam, which is 32.36m in height, 4m in crest width and 189.5m in crest length. The upstream and downstream slopes of dam are all with three-level changing slope. In the upstream, it is 1:3.25, 1:3.0 and 1:2.75 from bottom up; and in the downstream, it is 1: 1:1.5, 1:2.75, and 1:2.5, respectively. A detailed description of dam site and surrounding area is provided by Ning'er County Water Affair Bureau. The dam site is in a U-shape valley and its main lithology is purple shred siltstone, sandstone, feldspar-quartz sandstone, etc. And in the surrounding area, the hard bedrock is exposed.

Figure 1 Geographical position of Dahebian Reservoir and the area it effects

3. NUMERICAL SIMULATION

To earth dam, the main seismic damages are the cracks caused by the permanent deformation and inhomogeneous deformation, the reduction of the stability of dam caused by dynamic stress and strain, and the liquefaction of sand soil in the body and foundation of dam caused by great excess pore water pressure during the earthquake (Mi, et al., 2007). In this paper, the three-dimensional finite element method is used to simulate mathematically the permanent deformation and dynamic behavior of the earth dam system of Dahebian Reservoir. In order to create an accurate mathematical model of the physical prototype, the model comprises all the nodes, elements, material properties, real constants, and other features, which are based on the original datum of Dahebian Reservoir mentioned above.

3.1 Material parameters of the mathematic model

In the mathematical model, the earth dam and the rock mass around it as a whole are simulated (Fig. 2). The parameters of the earth dam are with reference to the characteristics of loess and the rock mass to weakly weathered granite as well. The exact value of the parameters is shown in table 1.

Table 1: Data for dam body and rock mass in the mathematical model

Material / Parameters	Young modulus	Poisson ratio	Density
Earth dam body	$2.8*10^{8}$	0.32	$2.0*10^{3}$
Rock mass in the lateral	$1.0*10^{10}$	0.38	$2.56*10^{3}$
Rock mass under the dam	$5.0*10^{9}$	0.35	$2.2*10^{3}$

As the main analysis object, more parameters of dam body are described in the follow:

- Shear transfer coefficient for open crack is 0.1.

Note: Typical shear transfer coefficients range from 0.0 to 1.0, with 0.0 representing a smooth crack (complete loss of shear transfer) and 1.0 representing a rough crack (no loss of shear transfer).

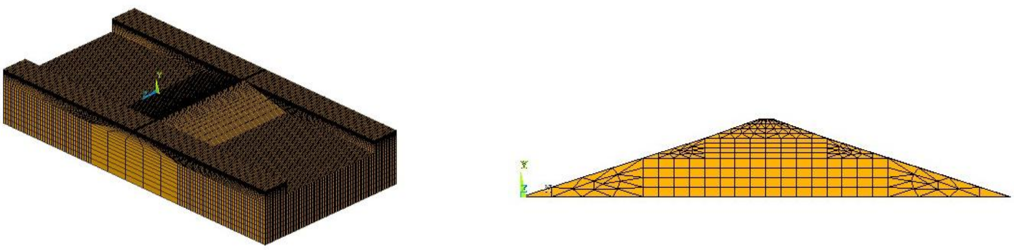
- Shear transfer coefficient for closed crack is 1.0.
- Uniaxial tensile cracking stress is 1.0×10^{6}.
- Uniaxial crushing stress is 1.2×10^{7}.

3.2 Scale parameters of the mathematic model

Based on the original datum of the earth dam system of Dahebian Reservoir, the shape and scale parameters of the model are selected.

The cross section of the dam is isosceles trapezoid, which is 32m in height, 5m in upper side width and 200m in lower side width (Fig. 2, b). The slope is 1:3.0, while the height changing between 0 to 24m. Other is 1:2.8. In longitudinal direction, the scale of the dam is 200m.

The rock mass under the dam is 50m deep; and its extensions with the stream are 100m both from the heel and the toe of the dam, while against the stream are 50m from the edge of lateral sides of the dam (Fig. 2, a).



(a) Earth dam and rock mass (b) cross section of dam body

Figure 2 Schematic diagram of the finite element model

3.3 Static analysis

The static analysis calculates the effects of steady loading conditions on the earth dam, while the steady inertia loads (such as gravity) are also included. According to the static analysis, the displacements, stresses, strains, and forces of the earth dam are determined.

3.3.1 Defining the boundary condition

On the two lateral faces in the X direction (that is with the stream), the displacements in the X direction are constrained. Well on the other two lateral faces, the same constrains are using in the Z direction. On the bottom of the rock mass, freedoms of all the directions are constrained.

3.3.2 External load

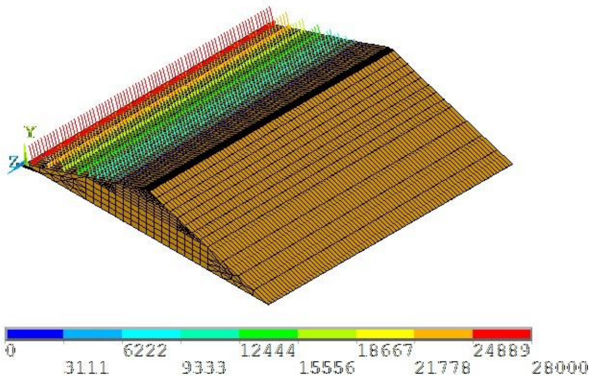
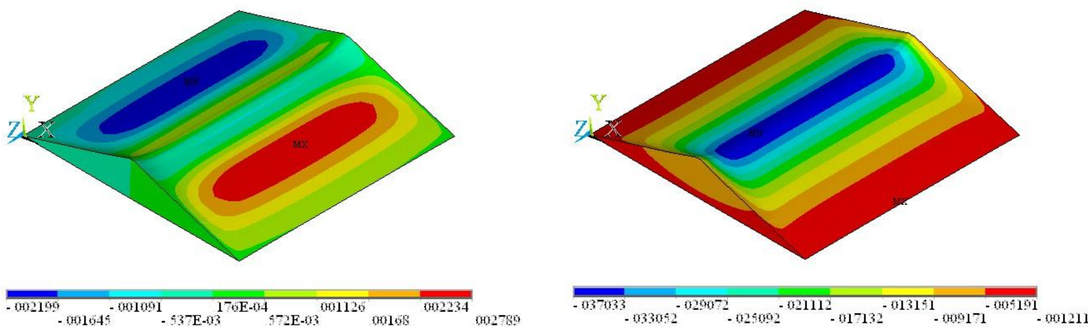


Figure 3 Triangle distributing load applied to the dam

The main external load of the dam is hydrostatic pressure. For the reservoir, its normal pool level is 29.41m. So the triangle distributing load, which maximum value is 2.8×10^{4}Pa is selected to simulate the hydrostatic pressure (Fig. 3).

3.3.3 Results of analysis

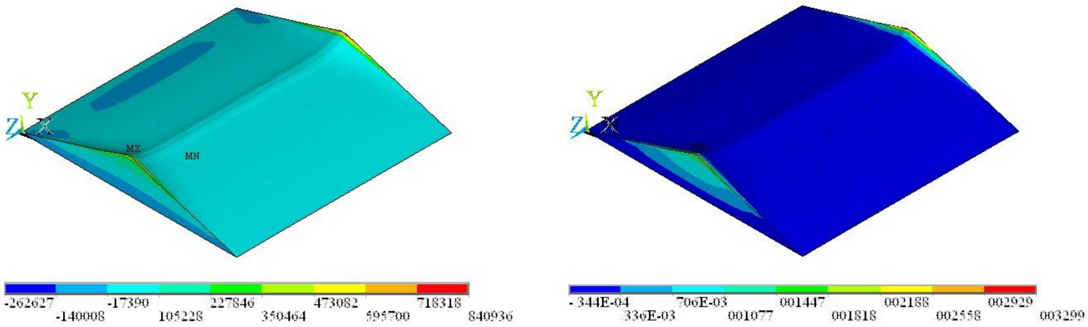
Under the hydrostatic pressure and deadweight of the dam, the maximum deformation of the dam body appeared in the middle part in X direction and in the upper part in Y direction (Fig. 4).



(a) X direction (b) Y direction

Figure 4 Deformation of the dam under hydrostatic pressure and gravity

The first principal stress is the maximum value of compressive stress. For the dam body, the greatest one appeared on left and right dam abutments (Fig. 5). For the strain, the situation is the same. Although the greatest value of first principal stress is 8.4×10^{5}Pa, which more less than the uniaxial crushing stress (1.2×10^{7}Pa), the distribution of the stress and strain must be paid enough attention.



(a) Stress (b) Strain

Figure 5 First principal stress and first principal strain

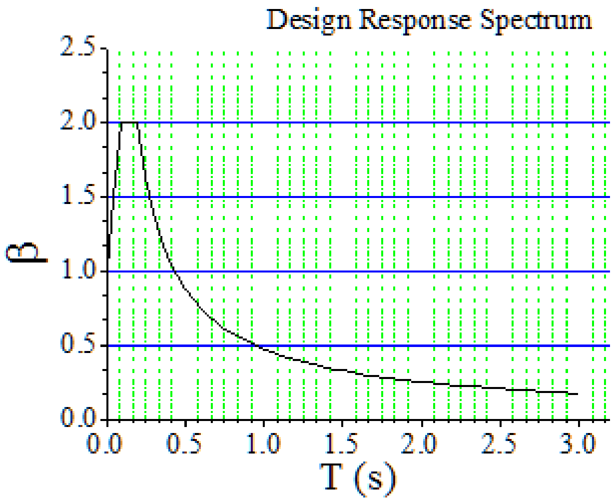
3.4 Dynamic analysis

3.4.1 Original datum

The basic modeling and boundary conditions are the same to situation in the static analysis. For spectrum analysis, only Young modulus and Poisson ratio are kept as material parameters.

3.4.2 Design response spectrum

To determine the response of the dam during earthquake, the spectrum analysis is used. According to *specifications for seismic design of hydraulic structures*, the representative value of response spectrum β_{max} is 2.0, and the characteristic period of the first kind of site T_g is 0.2. The formulae and curve of response spectrum are described as below (Fig 6).



$$\begin{cases} \beta = 10T + 1.0, & 0 < T \leq 0.1 \\ \beta = 2.0, & 0.1 < T \leq 0.2 \\ \beta = (0.2/T)^{0.9} \times 2.0, & 0.2 < T \leq 3.0 \end{cases}$$

Figure 6 Curve of design response spectrum

3.4.3 Results

Using the spectrum analysis, the displacements and internal forces under the response spectrum are calculated.

The distribution of deformation, stress and strain in different order are shown in the follow figures (Fig. 8 ~ Fig. 10). The positions of maximum value are similar to the cracks positions on the earth dam after the Ning'er Earthquake (Fig. 7).

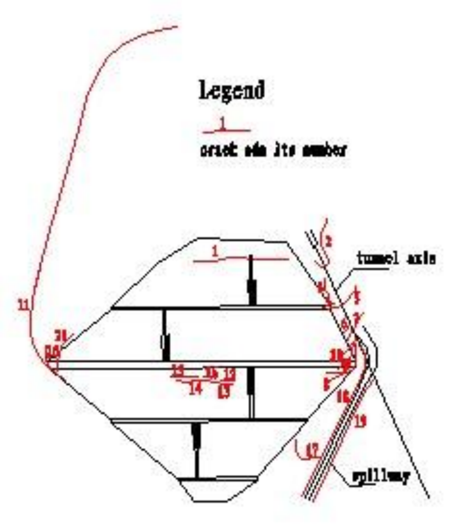


Figure 7 Cracks on the dam body

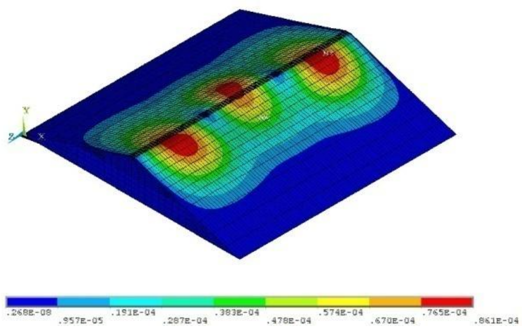


Figure 8 Deformation in the third order

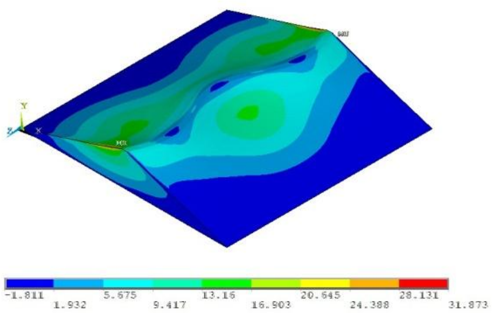


Figure 9 Stress in the fourth order

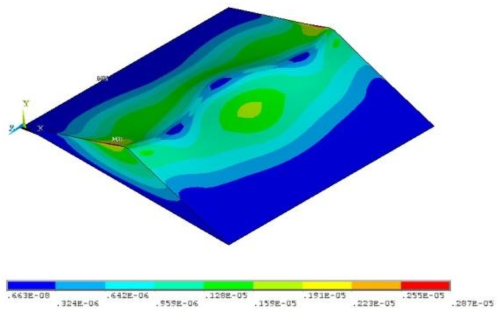


Figure 10 Strain in the fourth order

4 CONCLUSION

It is a complicated engineering problem for the dam's response during the earthquake. In order to solve the problem effectively, the numerical simulation must be combined with the engineering experience (Zhang, et al., 1989). According to the static and dynamic analysis, we can find that the middle part and abutment of the earth dam are the weak parts of anti-seism, and the results are reasonable while comparing with the actual earthquake disaster of the Dahebian Reservoir during the 2007 Ning'er Ms 6.4 Earthquake.

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