SEISMIC SAFETY DEGREE EVALUATION FOR STABILITY OF HIGH ARCH DAM ABUTMENT

LI TONGCHUN [1], DAI MIAOLIN[2], LI CHENG[3] and CHEN WEI[4]

[1] Professor, [2]Asso. Professor, and [3,4]Post Graduate of
College of Water Conservancy and Hydropower Engineering, Hohai University, Nanjing, China
E-mail: tongchun@jsmail.com.cn, mldai@mailsvr.hhu.edu.cn

ABSTRACT :

A new FEM seismic stability safety evaluation for high arch dam abutment is suggested in this paper. The shear strengths on the sliding surfaces are divided by different strength-reduction ratios and the seismic analysis is made after the accomplishment of the static analysis. The seismic safety factor is corresponding to that all the elements on the sliding surface are sliding under earthquake loads. The earthquake waves are put on the artificial boundaries and the viscous radiation conditions are used to simulate the outwards wave absorption. An example is given to explain how to evaluate the seismic stability safety for high arch dam abutment this method.

KEYWORDS: arch dam abutment, seismic safety stability, strength-reduction ratio, safety factor

1. INTRODUCTION

In west China, a lot of high arch dams are being or will be built. As the geological conditions of these dam sites are rather complex and the seismic intensity is very high, it is very important to evaluate the seismic safety degree for stability of high arch dam abutment. Rigid block ultimate equilibrium method is usually used to determine the safety factor against sliding for arch dam abutment. The disadvantage of this method is that the elastic and plastic material properties can’t be considered. When the earthquake is taken into account, the quasi-static forces are usually used to simulate the earthquake loads and the earthquake wave propagation properties can’t be considered.

Application of FEM, which are widely used in the analysis of static stability of arch dam abutment, can overcome the disadvantages of rigid block ultimate equilibrium method to some extent. The strength against sliding gradually decreased method based on FEM is used to determine the safety factor under the static loads by many researchers. The limit state is defined as that all the elements on the sliding surfaces are sliding.

When the earthquake process is simulated, some researchers take the ratio between the total force against the sliding and the total sliding force as the safety factor for the seismic stability analysis (Su Chao, 2003). By this method, the safety factor is calculated at every moment during the period of earthquake action. These safety factors are actually the reduction ratios of shear strengths on the sliding surfaces, that is, the margin of safety of the strength is different at different moment during the seismic action. However, the shear strengths are decreased mainly due to the time effectiveness, and the earthquake usually occurs only in a few seconds. In other words, the shear strengths can be taken as constants in the earthquake process. Therefore, this method is not very suitable to determine the safety factor for the seismic stability. According to above analysis, a proper method is searched for seismic stability safety evaluation of arch dam abutment in this paper, and combined with FEM calculation, an example is conducted in detail.

2. METHOD OF SEISMIC STABILITY SAFETY EVALUATION FOR ARCH DAM ABUTMENT

2.1. Definition of static safety factor for arch dam abutment

The solution of stability of arch dam abutment is normally referred as the determination of fields of stress, displacement, and strain under determined loads, which are satisfied with static balance equation, deformation coordination, proper constitutive relation, and strength criteria under special boundary conditions. The overall stability of arch dam abutment is usually defined in two following ways:

a. The ratio K between the overall force against the normal force:

$$K = \frac{P_{overall}}{P_{normall}} \tag{2.1}$$

Here: $P_{normall}$ is the normal load. $P_{overall}$ is the load under which the arch dam abutment is in the state of limit stability.

b. The strength-reduction *K*, just as all the elements on the sliding surfaces are sliding when the parameters of the shear strengths are as follows:

$$c_e = c/K \quad , \quad \tan\varphi_e = \tan\varphi/K \tag{2.2}$$

The above two safety factors are usually obtained by numerical methods, such as finite element, etc., and geomechanical model test.

2.2. Seismic stability safety evaluation for arch dam abutment

The substances existing in the weak discontinuity of rock mass have been changing in physical and chemical manner under the combined actions of mechanical field, hydraulic field, chemical field and thermal field. Accordingly, the shear strength of the weak discontinuity has been gradually decreasing and the stress field has also been changing. When earthquake occurs, seismic load is exerted on the dam abutment upon which a static stress field has existed. Earthquake may occur any time, but the initial mechanical property of rock mass and the static stress state are different at different times, so the strength safety margin of rock mass is also different. Furthermore, the earthquake usually occurs in a few seconds, and the shear strengths can be taken as constants in the earthquake process.

Based on the above analysis of action mechanism about earthquake load, a new method of numerical seismic stability safety evaluation for dam abutment is presented in this paper. The shear strengths on the weak discontinuities are divided by different strength-reduction ratios and the numerical seismic analysis is carried out after the accomplishment of the static analysis. As the duration of earthquake is usually very short, the shear strengths can be considered as constants in the earthquake process. Under the different shear strength-reduction ratios, the distribution characters of deformation, stress, and plastic zone is analyzed. The influence of the shear strength-reduction ratios to displacement and failure situation is also analyzed. The safety factor of seismic stability for arch dam abutment is finally determined on the basis of static analysis results, and the dynamic safety situation is evaluated.

3. FEM ANALYSIS OF SEISMIC STABILITY FOR ARCH DAM BUTMENT

At the present time, the ordinary numerical methods used in the research on the stability of rock mass are finite element method (FEM), boundary element method, weighted residual method, distinct element method, rigid element method, discontinuous deformation analysis method, numerical manifold method and so on. Among them, the front four methods base on the continuum mechanics theory and the subsequent three methods base on the discontinuous medium mechanics theory.

FEM is widely used in the static and dynamic analysis for rock mass (Zhu Bofang, 1998). Analysis of static and dynamic stability for arch dam abutment can be carried out by this method, in which any non-linear constitutive relation can be specified, and the joint element can be used to analogue the slip and separation along the sliding surfaces (Yao Weiming, 1999). In the nonlinear dynamic calculation, the dynamic balance equation in the incremental way at the special moment is as follows:

$$[M]\{\Delta\ddot{\delta}\}+[C]\{\Delta\dot{\delta}\}+[K]\{\Delta\delta\}=\{\Delta P\} \tag{3.1}$$

Here: $\{\Delta\ddot{\delta}\},\{\Delta\dot{\delta}\},\{\Delta\delta\}$ and $\{\Delta P\}$ are the increments of acceleration, velocity, displacement and load. $[M]$, $[C]$ and $[K]$ are the matrix of mass, damping, and stiffness. Rayleigh damping is chosen, and $[C]$ can be defined as follows:

$$[C]=\alpha[M]+\beta[K] \tag{3.2}$$

Eqn. 4.1 is solved with Wilson- θ method. In order to avoid reflecting phenomenon that is created by earthquake wave in the boundaries, the earthquake waves are put on the artificial boundaries and the viscous radiation conditions are used to simulate the outwards wave absorption (He Xiangli, 2007).

4. SEISMIC SAFETY EVALUATION FOR STABILITY OF A HIGH ARCH DAM ABUTMENT

4.1. Calculation model and parameters

As showed in Figure 1, an arch dam which is 284m high will be built in west China. The part of the left arch abutment is showed in Figure 2. The rock mass is divided into several blocks by nearly horizontal and vertical weak seams, and their physical and mechanical parameters are listed in Table 1. The following are the seismic parameters selected: the reference period is 50 years, its exceeding probability is 10% , the corresponding horizontal seismic peak acceleration is 0.165g. On the basis of above parameters, the time-acceleration curve was made by artificial work according to the response spectrum (DL5073-2000, 2001). The duration of earthquake is 15s.

A calculation model of FEM is created for the dam and the abutment. The model is meshed by tetrahedron element with 4 nodes for the rock mass, and by hexahedron element with 8 nodes for the dam. Rock masses are considered as elastic material. The joint elements are used to simulate the weak seams, where Mohr-Column strength criterion is selected for the normal direction and no tensile stress strength criterion for the tangential direction. Rayleigh damping is chosen in the dynamical calculation. The seismic acceleration is exerted on the bottom of the model, and artificial boundaries are used to avoid the reflection of seismic waves. The weight of the rock mass and the dam is taken into account, and the pressure of the water is ignored. Because the stability of the left abutment is poor than that of the right, the research is focused on the left abutment.

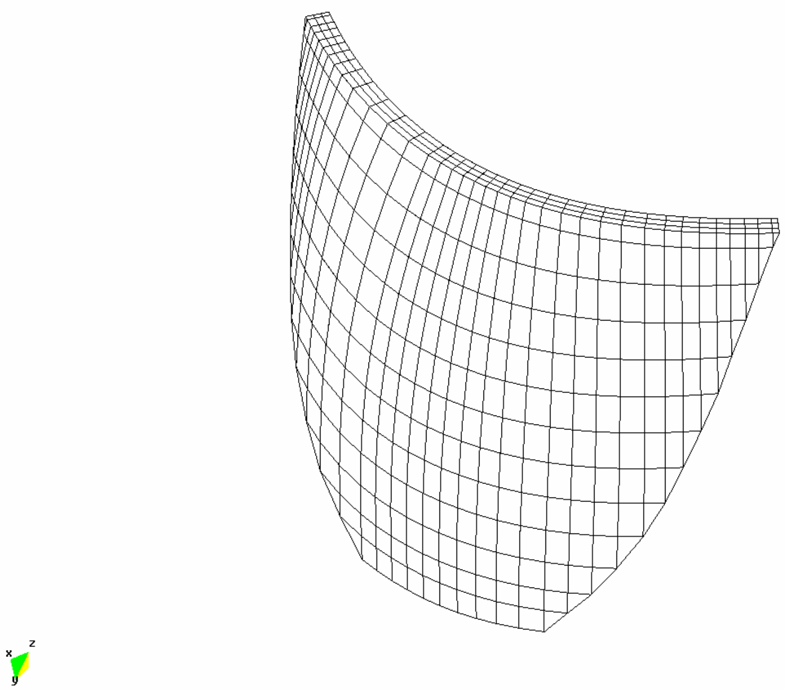

Figure 1 Arch dam and its mesh view

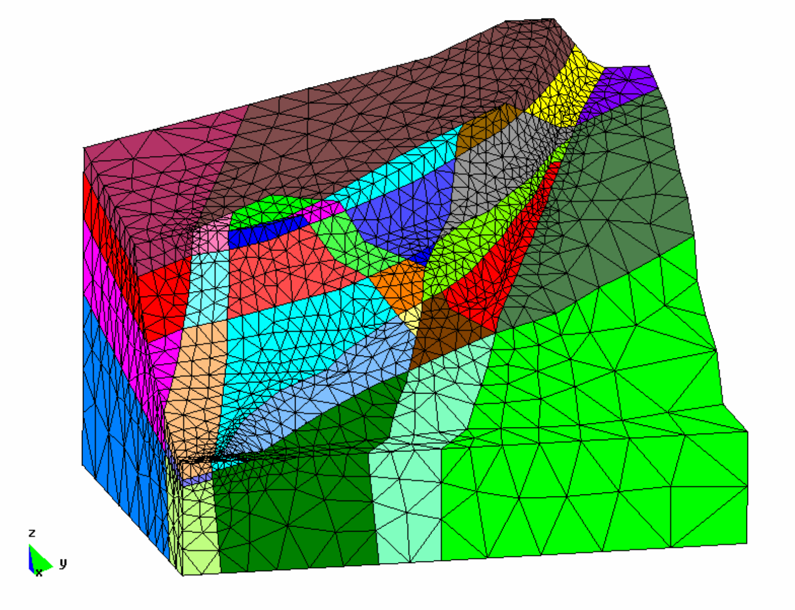

Figure 2 Part of left arch dam abutment

Table 1 Parameters of weak seam

	Horizontal		Vertical	
Weak seam	C3-1	LS337	F114	F33
Elastic modulus (GPa)	0.25	1.15	1.15	1.15
Poisson ratio	0.36	0.35	0.35	0.35
Friction factor	0.30	0.35	0.35	0.35
Cohesion c (MPa)	0.03	0.04	0.05	0.05

Table 1 Parameters of rock mass

Zone	Above C3-1	Between C3-1 and S337	Below LS337
Elastic modulus (GPa)	7	17	0.27
Poisson ratio	0.27	0.25	0.22
Bulk density(kN/m3)	25	27	28

A calculation model of FEM is created for the dam and the abutment. The model is meshed by tetrahedron element with 4 nodes for the rock mass, and by hexahedron element with 8 nodes for the dam. Rock masses are considered as elastic material. The joint elements are used to simulate the weak seams, where Mohr-Column strength criterion is selected for the normal direction and no tensile stress strength criterion for the tangential direction. Rayleigh damping is chosen in the dynamical calculation. The seismic acceleration is exerted on the bottom of the model, and artificial boundaries are used to avoid the reflection of seismic waves. The weight of the rock mass and the dam is taken into account, and the pressure of the water is ignored. Because the stability of the left abutment is poor than that of the right, the research is focused on the left abutment.

4.2. Dynamic stability analysis

4.2.1.Static stability analysis

After the shear strength parameters of the weak seams have been divided by the strength-reduction ratios K from 0.8 to 1.25, the static stability calculation of the dam abutment is carried out by FEM for each strength-reduction ratio. Figure 3 shows the relationship between the strength-reduction ratios K and displacements δ of the exposed points on the horizontal weak seams in the left abutment. As shown in the figure, when the strength-reduction ratio K is less than 1.00, the left abutment is basically in the linear elastic state. When K is greater than 1.0, the change rates of the displacements with K increase obviously. The structure situation of the left abutment has changed greatly when K reaches 1.0, so 1.0 can be regarded as the safety factor of static stability of the dam abutment.

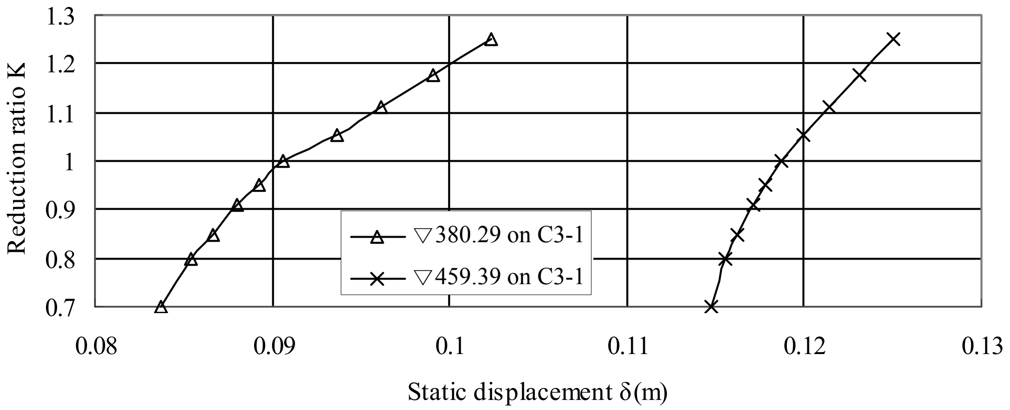

Figure 3 Reduction ratio K with static displacement of exposed points on weak seam

4.2.2.Dynamic stability analysis

Based on the static analysis result of strength-reduction ratio K, dynamic stability analysis is separately carried out under seismic load. By selecting the permanent displacement of every strength-reduction ratio at the final moment (the fifteenth second) of the seismic action, the variation of displacement with strength-reduction ratio K is plotted in the Figure 4. As shown in the Figure, when the strength-reduction ratio is less than 0.9, the left dam abutment is basically in the linear elastic state, and the trend of large deformation is obvious when K is greater than 0.9. Therefore, 0.9 can be regarded as the dynamical stability safety factor.

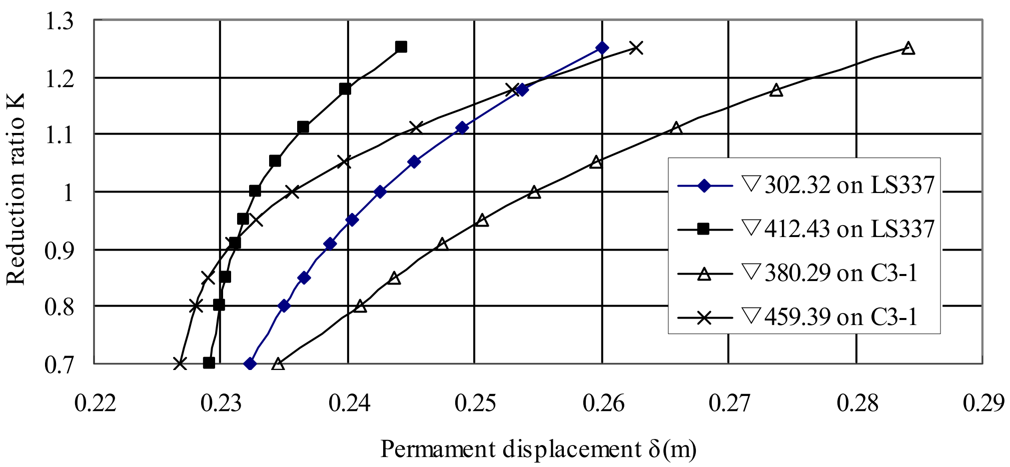

Figure 4 Reduction ratio K with permanent displacement of exposed points

5. CONCLUSIONS

The method of numerical seismic stability safety evaluation for arch dam abutment proposed in this paper can be concluded that the numerical seismic stability should be conducted after the static analysis has been finished by strength against sliding gradually decreased method, and that the seismic safety factor can be defined as the strength-reduction ratio of shear when the stability of the dam abutment is in the limit state. The analysis of an example shows that the method presented in this paper is effective for seismic stability safety evaluation of arch dam abutment.

REFERENCES

DL5073-2000 (2001). “Specifications for Seismic Design of Hydraulic Structures”. China Electrical Power Press, China

He Xiangli and LI Tongchun. (2007). Numerical analysis of seismic wave-motion of gravity dam in time domain. *Journal of Hohai University* **35:1,**5-9.

Su Chao, LI Junhong and REN Qingwen. (2003). FEM-based dynamic stability analysis of abutment for high arch dams. *Journal of Hohai University* **31:2,**144-147.

Yao weiming, Li Tongchun and Ren Xuhua. (1999). Elasto Plastic FEM Analysis for Rock Mass with Weak Seams. *Journal of Hohai University*, **27:5**: 34-38

Zhu Bofang. (1998). The Finite Element Method Theory and Applications. China Water Conservancy and Hydropower Press, China