Dynamic stability of dams against Deep Slide by strength reduction method

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ABSTRACT :
In this paper ,the commercial finite element software ADINA is used to analyze dynamic stability of dams. Based on the analysis of action mechanism about the dam foundation under earthquake load，a new numerical method of dynamic stability against deep slide is proposed. The shear strength of the sliding surface is divided by different strength reduction factor and the numerical seismic analysis is carried out after the accomplishment of the static analysis. Under the different shear strength reduction factor, the curve about the earthquake total displacement of the key point and strength reduction factor is focused, according to the curve mutation, the distribution of plastic zone in the foundation and the non-convergence of the finite element calculation. The dynamic stability safety factor is finally defined as the strength reduction factor of shear strength when the gravity dam is in the critical stability state under earthquake load. As an application example of the above concepts，the dynamic stability safety for a gravity dam in a hydropower project is evaluated. The analysis of the example shows that the proposed method is feasible and it provides a valuable way for dynamic stability safety evaluation

KEYWORDS:
dynamic stability; strength reduction; dams; displacement; ADINA

1.Introduction

China is a multi earthquake country. Many important hydraulic projects are built in the high-intensity earthquake zone. There are high mountains and steep slopes in these zones, earthquake-induced instability and the collapse of the slide is a common disaster. The dam stability under earthquake is a comprehensive topic which involves earthquake engineering, seismic, engineering geology, soil dynamics, and many other disciplines, this comprehensive topic is also one of the problems which is very concerned by the earth's environment and geotechnical engineering, the earthquake response is related with the enter seismic characteristics, the mechanical properties of rock and sliding surface and many other ratios, so dynamic analysis is far more complex than static analysis.

Recently, the methods which are often used for seismic stability are Pseudostatic analysis, Newmark sliding block analysis and finite element calculations. Pseudostatic analysis can not reflect the seismic wave propagation, Newmark sliding block analysis is too rough because of its too much simplification, the two methods all have some shortages..

FEM calculation method can reflect the mechanical properties of complex rock, it has been successfully applied to more static stability analysis (GE Xiurun et al.,2003), and has also made considerable progress in dynamic calculation research (LI Haibo et al., 2003; DAI Miaolin et al., 2007), can make up for the lack of rigid body limit equilibrium method to a certain extent, but the FEM is more confined to get the stress, displacement and plastic zone of rock, especially for how to obtain the model seismic stability factor of safety, has not been very good solution. Safety factor time history analysis method uses the method of the static stability safety factor calculation (LIU Hanlong et al.,2003; WU Zhaoying et al.,2004), according to the anti-sliding force and sliding force of every moment, the stability factor of safety of the corresponding moment is obtained, because the direction and value of earthquake acceleration is rapidly changed with time, when the safety factor of one moment is less than 1 does not necessarily mean that the overall slope is instable, it may only means that the earthquake permanent deformation is increasing, the evaluation criteria for safety factor time history analysis method can not be determined easily. The safety factor time history analysis method also has one problem: the safety factor of each moment in earthquake is the reduction coefficient of corresponding moment when the sliding surface in limited state, it means that the shear strength of sliding surface of each time is not the same, actually, earthquake often happens in a very short period of a few seconds, the shear strength of sliding surface Can be considered unchanged in earthquake, in this sense, the safety factor time history analysis method appears to be not entirely consistent with the actual situation. For these reasons, according to the dam deep seismic instability mechanism, the analysis method of seismic stability under earthquake load is focused in this paper.

2. The safety evaluation criterion of seismic stability based on strength reduction method

Recently, there are three major discrimination criterions(J. M. Chandra Kishen et al., 2001)of the dam foundation deep sliding failure based on the strength reduction method: (1) Given the convergence criteria, the instability state is identified according to the convergence of FEM calculation, that is, given the number of non-linear iteration and limits, if the largest displacement or the residual of unbalanced force can not meet the required conditions for convergence, then it is considered that the dam foundation is instable; (2) The state of instability is determined according to the variation characteristics of relationship curve about the strength reduction factor and the displacement of a certain part within the calculation region, when the strength reduction factor increases to a particular value, the displacement of a certain part enlarges suddenly, the inflection point appears on the curve, the dam foundation is instable; (3) Judging through the change and distribution of certain parameters within the region, such as the broad shear strain, when the plastic zones are connected, the dam foundation is instable. In the above-mentioned three criterions, the first criterion is used by more scholars, but the limit of the convergence condition and the iteration number is very different, and the different convergence criteria will directly cause the different safety ratios. The physical concept of second criterion is clear, but the results will be affected by the iteration number and the permissible limits, when the permissible limits is larger, the precision is low, and the displacement values are not accurate, there will be deviations when the safety factor is determined. The third criterion is determined by the plastic strain amplitude, if the amplitude is taken large, the instable state may be defined as stable state or limit equilibrium state, the safety factor of deep stability against sliding can not be obtained. In a word, the above-mentioned three criterions are all not perfect. Based on the above-mention reasons, the criterion is focused in this paper can be expressed as（1）+（2）+（3）.It means that, given a convergence criterion for calculation, when calculation is finished, the curve about the displacement values of dam foundation key points and strength reduction ratios is drawn($D-K$ curve), and the plastic zone is observed, then the safety factor is obtained by integrating the three mentioned steps.
The shear strength reduction factor method has been successfully applied to the static stability analysis of complex rock slope (ZHAO Shangyi et al., 2003). Mohr-Coulomb criterion is generally used for the strength criterion of sliding surface, and its major parameters are shear strength parameters such as Cohesion (c) and internal friction angle (ϕ), the steps of shear strength reduction method are as follows: suppose the shear strength parameters are c and ϕ, K is the strength reduction factor. When K=1, the strength need not to be reduced; When K=2, c and ϕ must to be reduced synchronously (the other parameters are not changed, such as the elastic modulus), then these new values are used into finite element calculation; Similarly, when K is equal to any other values, the new values can be got as follows（Zuyu Chen,2003):

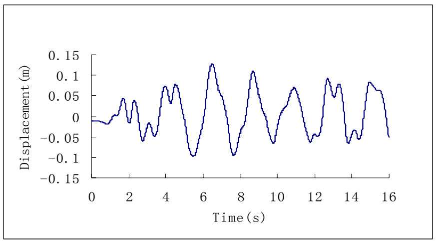
$$c' = c \ / K , \qquad \phi' = \arctan(\tan\phi / K) \tag{2.1}$$

Actually, before the earthquake, rock under the action of stress field, seepage, chemical and temperature fields and other external environment, the material of the Sliding surface will be in physical and chemical changes, as time goes by, the shear strength of sliding surface will be reduced accordingly, and the stress state of rock will be correspondingly changed., when the earthquake happens, the earthquake dynamic load is on the basis of static state. Earthquakes occurs at any time, before the earthquake, the mechanical properties and static stress of rock are not the same at different time, and the strength reduction ratios are not the same. On the basis of analysis on the seismic loading mechanism, one method is focused to study the deep seismic stability of dam foundation in this paper, the method is as follows: First use the equation 1 to reduce the shear strength of the sliding surface for static analysis, based on the static analysis, seismic load is imposed for a dynamic analysis, because the period of the earthquake is very short, the rock material strength can be assumed remain the same the in the process of earthquake. Through the use of different strength reduction ratios, rock deformation and stress distribution, the size and distribution of plastic zone, convergence in the process of calculation, the iteration number and the change law of the relationship curve about the permanent displacement with the strength reduction factor are analyzed, then the damage pattern of rock foundation is understood and the material strength reduction factor of the limit stable state is defined the safety factor.

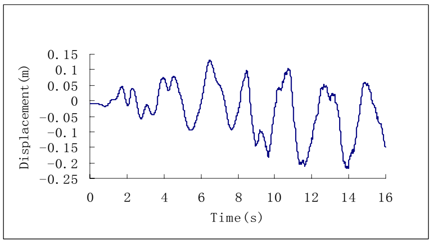
It should be noted that:

(1)The selection of key points: in seismic stability problems, the selection is not easy the same as in static problem, the selection is unreasonable and even sometimes is wrong depending on experience alone. It is suggested here that the key points of static stability problems should be selected initially, such as the dam crest and dam heel points, then along the surface which is easy to be dynamic instable, select the points, select more points, observe the *D-K* curves of these points, if a curve has unstable fluctuation, the point is taken as the key point (Fig 1b).

(2)How to take the displacement value: Because the direction and value of earthquake acceleration is rapidly changed with time, it is suggested that the displacement of key points at the end of time history can be taken for the *D-K* curves. By the mutation of the curve, the stable safety factor is obtained, then the instable shape can be seen by observing the distribution of plastic zone and plastic strain.



a. Stable fluctuation



b. Unstable fluctuation

Figure 1 The selection of key points

3. Analysis of examples

3.1 The general situation of project and calculation parameters

Suppose there is sliding surface in the gravity dam (Fig.2), in order to understand the impact of earthquake load on the dam and power station, it is needed to study the seismic stability of this dam. The material of this model can be divided into 3 species, which is dam body, sliding surface and foundation. The elastic modulus of dam is 10GPa, poisson ratio is 0.167, and density is 2400kg /m^3; The elastic modulus of foundation is 1GPa, poisson ratio is 0.25, and density is 2500kg /m^3. The specific mechanical parameters of sliding surface are shown in Table 1. The elastic modulus is increased by 30% in dynamic calculation, only the horizontal earthquake action is considered in the calculation, the EI-Centro seismic wave is used to enter to input from the underside of the foundation. Computing time step is 0.02 second, the total computing time is 16 seconds. The seismic wave time history curve is illustrated in Figure 3.

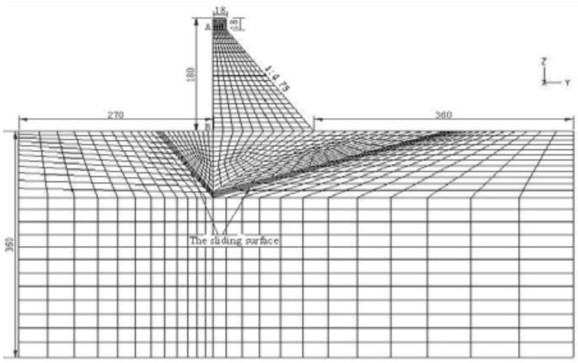


Figure 2 Mesh of the model and key points

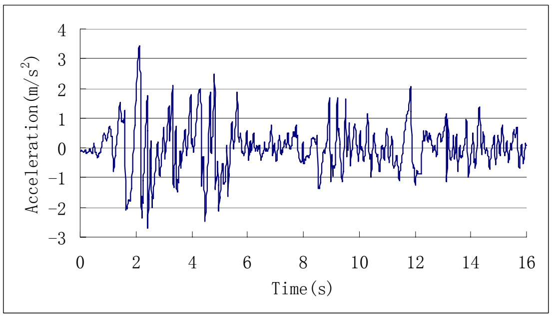


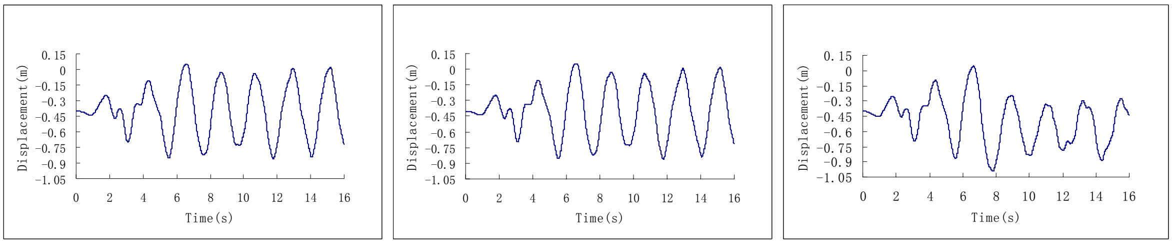
Figure 3 The EI-Centro seismic wave

Table 1 Material parameters of sliding surface

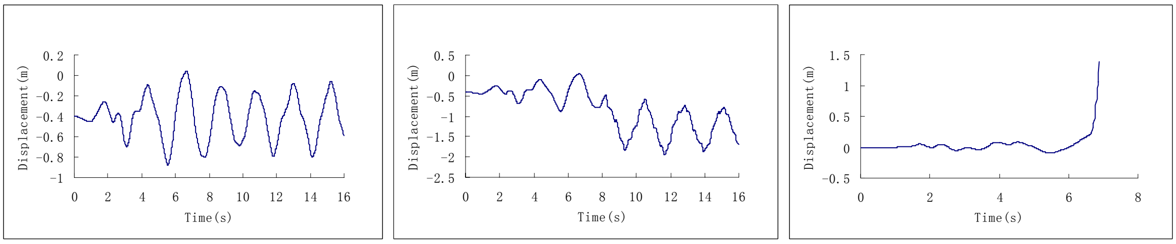
c / kPa	ϕ /(°)	γ /(kN × m^{-3})	E / kPa	υ
42.0	17.0	20.0	1.0×10^5	0.3

3.2 seismic stability safety analysis

In this paper the restart of ADINA is utilized (ADINA R & D, Inc;2005). The numerical seismic analysis is carried out after the accomplishment of the static analysis which includes the gravity of rock .Consideration of the whole seismic stability safety factor of slope under earthquake load less than 1,during the analysis of strength-reduction method, the strength reduction factor should take a value less than 1 before carrying on static and dynamic calculation under various multiple of reducing strong. The model dynamic displacement time-history under earthquake load which is used to analyze the dynamic response results and stability of gravity is calculated. The dynamic displacement time-history on several key locations is analyzed. The key point A and B is taken from crest and dam heel respectively (Fig.2). Figure 4 and Figure 5 show horizontal displacement time-history of point A and point B respectively under different strength-reduction ratios.

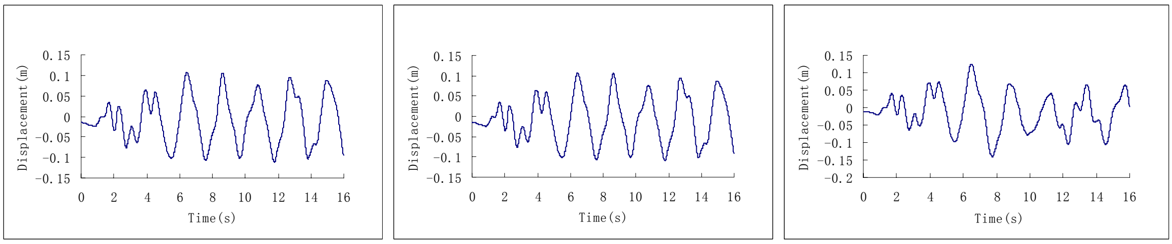


a. K=0.724　　b. K=0.82　　c. K=1.012

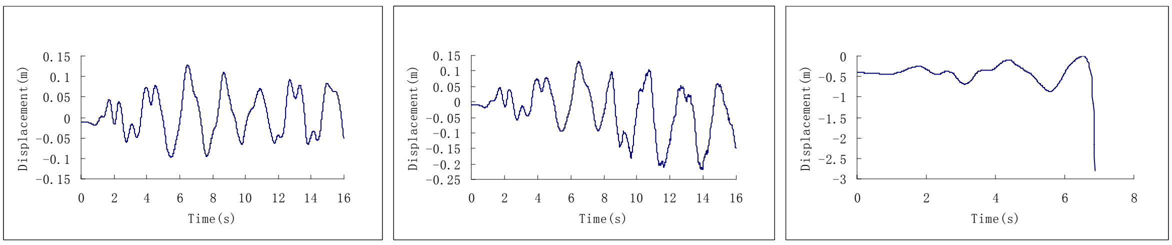


d. K=1.102　　e. K=1.136　　f. K=1.203

Figure 4　The horizontal displacement time histories of A point Under different K



a. K=0.724　　b. K=0.82　　c. K=1.012



d. K=1.102　　e. K=1.136　　f. K=1.203

Figure 5　The horizontal displacement time histories of B point Under different K

As shown in Figure 4 and Figure 5, the dynamic displacement time-history of point A and point B produces mutation when the strength-reduction ratio is between 1.136 and 1.203.When the strength-reduction ratio is 1.203, the calculation is non-convergence and the displacement time-history produced a unidirectional irreversible macro mutation. According to the analysis method of this paper, the dam foundation occurred unstable failure when the strength-reduction ratio is certain value between 1.136 and 1.203. Figure 6 shows plastic zone distribution in sliding surface of dam foundation and the whole plastic zone yields at this time. Taking point B as the key point, the relation curve between shear strength-reduction ratio and displacement of key point is established (*D*—*K* curve), see Figure 7.

As shown in Figure 7, when the strength-reduction ratio is 1.136 under dynamic condition, permanent displacement under horizontal shock in point B produces mutation and the seismic stability safety factor for a gravity is thought as 1.136.The Figure 8 shows the instable shape.

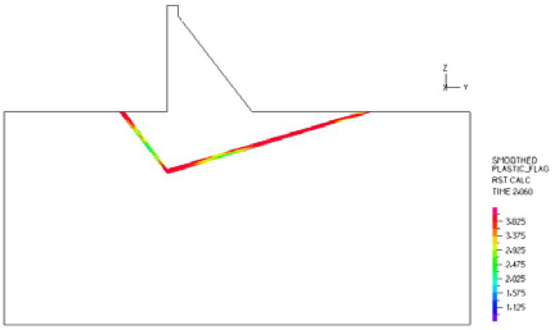


Figure 6 The plastic zone when *K*=1.136

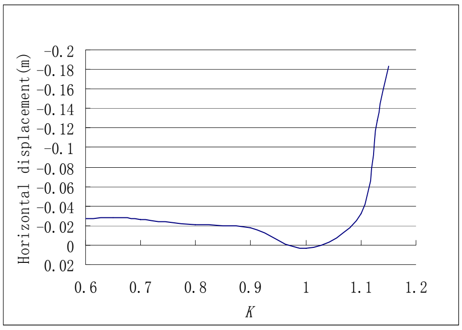


Figure 7 *D*—*K* curve of point B

4. Conclusions

How to evaluate scientifically the seismic stability safety factor of dam foundation according to the calculation results based on finite element, which is an important problem encountered for the application of Finite Element Method in rock engineering. In order to study on the physical mechanism of inflection point appearing on the relation curve between permanent displacements of key point and the value of K, after the shear strengths reduced by different multiple of reducing strong, the static analysis and the dynamic analysis are executed. When the calculation is non-convergence , the inflection point appears on the curve of displacement on control point, the failure region of element on sliding channel completely connects nearly and the whole sliding channel is formed nearly, the values K is thought as the seismic stability safety factor at this time. This method provides a new thought for the study of seismic stability.

It should be noted that the standard applied in this paper for taking values of the allowable minimum seismic stability safety factor needs to make further research in order to make it consistent with related design safety standard(DL5180–2003).

Convergence criterion should be elected according to practical problems. When the structure or component is hardened badly, a minor structural deformation will bring a quite large exterior load or when the norm ratio of displacement increment on the adjacent iteration has a large leap,

the convergent problem will be thought as non-convergence, at which the displacement convergence criterion should not be considered. The convergence criterion should be selected properly on calculation, which has an important influence on the calculation results. The displacement convergence criterion of ADINA is adopted in this paper. The comparative calculation shows that the calculation results will be closer to actual when the displacement convergence criterion is applied to the ideal elastic-plastic problem.

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