Seismic stability safety evaluation of gravity dam with shear strength reduction method

Da-sheng WANG*¹, Liao-jun ZHANG², Jian-jun XU¹, Ming-jie HE¹, Wei-di ZHANG¹

¹. East China Investigation & Design Institute, Hangzhou 310014, P. R. China
². College of Water Conservancy and Hydropower Engineering, Hohai University, Nanjing 210098, P. R. China

Abstract: A new method of numerical seismic stability safety evaluation for a rock slope is proposed based on the analysis of a gravity dam foundation subjected to earthquake loading. The shear strengths of the weak discontinuities are divided by different shear strength reduction ratios (K) and numerical seismic analysis is carried out after the static analysis is completed. With different K values, the curves of the permanent horizontal displacement of key points of the dam foundation (K-displacement curves) are studied. According to the curve change, the distribution of plastic zones in the foundation, and the slow convergence of the finite element method (FEM), the seismic stability safety factor is defined as K when the gravity dam is in the limit equilibrium state subjected to earthquake loading. These concepts were applied to the evaluation of seismic stability safety of a gravity dam for a hydropower project. The analysis of the example shows that the proposed method is feasible and is an effective method of seismic stability safety evaluation.

Key words: dynamic stability; shear strength reduction ratio; gravity dam; permanent horizontal displacement; ADINA system

1 Introduction

China experiences frequent earthquakes. Many important hydraulic projects are built in high-intensity earthquake zones, which have high mountains and steep slopes, and where earthquake-induced instability and collapse of the slide is a common problem. Gravity dam stability during earthquakes is a comprehensive issue that involves earthquake engineering, geological engineering, soil dynamics, and many other disciplines. The response to an earthquake is related to the seismic characteristics, the mechanical properties of rocks and sliding surfaces, and many other factors (Ghanaat 2002; Chopra and Zhang 1991), so dynamic analysis is far more complex than static analysis.

In recent years, the methods used to evaluate seismic stability have tended to be pseudostatic analysis, Newmark sliding block analysis, and the FEM. The first two methods have some shortcomings: pseudostatic analysis does not reflect the seismic wave propagation, and Newmark sliding block analysis is too rough because of oversimplification (Leger and
The FEM reflects the mechanical properties of complex rock systems (Zienkiewicz and Taylor 1989). It has been successfully applied to static stability analysis (Ge et al. 2003), and has also contributed to the considerable recent progress in dynamic calculation research (Li et al. 2003; Dai and Li 2007). The FEM can make up for the shortcomings of the rigid body limit equilibrium method to a certain extent, but it is confined to obtaining the stress, displacement and plastic zone of the rock. Especially when it comes to obtaining the model’s seismic stability safety factor, the FEM has not produced very good solutions. Time history analysis of the safety factor uses the method of static stability safety factor calculation (Liu et al. 2003; Wu et al. 2004). Because the direction and value of earthquake acceleration changes rapidly, the safety factor of each moment is obtained according to the anti-sliding force and sliding force of the same moment. When the safety factor of one moment is less than 1, it does not necessarily mean that the overall slope is unstable; it may only mean that the permanent deformation induced by the earthquake is increasing. The evaluation criteria for the time history analysis of the safety factor cannot be determined easily (Chandra 2005). The time history analysis of the safety factor has a problem: the safety factor of each moment in an earthquake is the reduction coefficient of a corresponding moment when the sliding surface is in a limited state, which means that the shear strength of the sliding surface is not the same from one moment to the next. Actually, an earthquake often occurs over a period of only a few seconds, so it can be assumed that the shear strength of a sliding surface remains unchanged.

In this sense, the time history analysis of the safety factor is not entirely consistent with actual conditions (Calayir et al. 1996; Cervera et al. 1995; Ghrib and Tinawi 1995). For these reasons, this paper focuses on the analysis of seismic stability subjected to earthquake loading according to the deep seismic instability mechanism of the dam (Priscu et al. 1985).

2 Safety evaluation criteria of seismic stability based on shear strength reduction method

There are three major discrimination criteria (Chandra and Singh 2001) for dam foundation deep sliding failure based on the shear strength reduction method: (1) Given the convergence criteria, the instability state is identified according to the convergence of the FEM; that is, given the number of nonlinear iterations and limits, if the largest displacement or the residual of unbalanced force meets the required conditions for convergence, then the dam foundation is considered unstable. (2) The state of instability is determined according to variation of the curve of the relationship between the strength reduction factor and the displacement of key points within the calculation region; when the strength reduction factor increases to a particular value, the displacement of a point suddenly grows larger, inflection appears on the curve, and the dam foundation is unstable. (3) Judging by the change and distribution of certain parameters within the region, such as the broad shear strain, the dam...
foundation is unstable when the plastic zones are connected.

The first of the three criteria described above is used by more scholars, but the convergence criteria and the number of iterations are quite different, and the different convergence criteria directly lead to different safety factors. The physical concept of the second criterion is clear, but the results are affected by the iteration number and the permissible limits; when the permissible limits are 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 plastic strain amplitude is large, the unstable state may be defined as a stable state or a limit equilibrium state, and the safety factor of deep stability against sliding cannot be obtained. In a word, the aforementioned three criteria are all imperfect. For these reasons, a new criterion was developed by synthesizing these three criteria. When the calculation is finished, and given a specific convergence criterion, the $K$-displacement curve and the plastic zone are observed. Then, the three criteria described above are integrated to obtain the safety factor.

The shear strength reduction method has been successfully applied to static stability analysis of a complex rock slope (Zhao et al. 2003). The Mohr-Coulomb criterion is generally used as the strength criterion of a sliding surface, and it relies on shear strength parameters such as cohesion ($c$) and the internal friction angle ($\phi$). The steps of the shear strength reduction method are as follows: The shear strength parameters are assumed to be $c$ and $\phi$, and $K$ is the strength reduction factor. When $K = 1$, the strength need not be reduced; when $K = 2$, $c$ and $\phi$ must be reduced simultaneously (the other parameters, such as the elastic modulus, are not changed). Then, these new values are used in the FEM. Similarly, when $K$ is equal to any other values, the new values can be obtained as follows (Chen 2003):

$$c' = \frac{c}{K} \quad (1)$$

$$\phi' = \arctan \left( \frac{\tan \phi}{K} \right) \quad (2)$$

When an earthquake occurs, its dynamic loading is based on the static state. Earthquakes can occur at any time. Before an earthquake, the mechanical properties, the static stress of rock, and the $K$ values are not the same as they are at different times. A method that focuses on the deep seismic stability of the dam foundation on the basis of analysis of the seismic loading mechanism can be developed as follows: First, Eq. (1) and Eq. (2) are used to reduce the shear strength of the sliding surface for static analysis. Based on the static analysis, a seismic load is imposed for a dynamic analysis. Because the period of the earthquake is very short, the rock strength is assumed to remain the same throughout the earthquake (Clough and Penzien 1993). The pattern of damage to the rock foundation can be understood through the study of different $K$ values, rock deformation, stress distribution, the size and distribution of the plastic zone, the convergence in the process of calculation, the iteration number, and the changes in the
relationship between the permanent horizontal displacement and the strength reduction factor.

The material strength reduction factor of the limit stable state is defined by the safety factor.

It should be noted that:

(1) The selection of key points is not the same in seismic stability analysis as it is in static problems. The selection may be unreasonable or even incorrect if it depends on subjective experience alone. Points such as the dam crest and dam heel points should be selected at the outset. Then, other points are selected along the surface, which tends to be dynamic and unstable. The dynamic horizontal displacement time histories of these selected points are observed (Fig. 1). Fig. 1(a) shows stable fluctuation in contrast with unstable fluctuation. The points that have curves with unstable fluctuation are considered key points (Fig. 1(b)).

(2) Because the direction and value of earthquake acceleration change rapidly with time, the permanent horizontal displacement of key points at the end of the time history can be used for drawing the $K$-displacement curves. The stable safety factor is obtained from the variation of the curve. Then, the unstable shape can be observed in the distribution of the plastic zone and plastic strain.

![Fig. 1 Dynamic horizontal displacement time histories of selected points](image)

3 Analysis of examples

3.1 General situation of project and calculation parameters

Suppose there is a sliding surface in the foundation of a gravity dam. In order to understand the impact of earthquake loading on the dam and power station, it is necessary to study the seismic stability of the dam. A model was built with plane-strain elements. It has 1522 elements and 1735 nodes. The height of the dam is $H = 180$ m, the length of the upstream foundation is 1.5 times $H$, the length of the downstream foundation is 2 times $H$, and the depth of the foundation is 2 times $H$ (Fig. 2). The study areas of this model can be divided into three parts: the dam body, the sliding surface, and the foundation. The elastic modulus of the dam is 10 GPa, the Poisson ratio is 0.167, and the density is 2400 kg/m$^3$. The elastic modulus of the foundation is 1 GPa, its Poisson ratio is 0.25, and its density is 2500 kg/m$^3$. The sliding surface is made of Mohr-Coulomb material whose cohesion is 42.0 kPa; the internal friction angle is 17.0°, the density is 2000 kg/m$^3$, the elastic modulus is 0.1 GPa and the Poisson ratio is 0.3. The elastic modulus increased by 30% during the dynamic calculation. Only the horizontal earthquake force was considered in the calculation. The EI Centro seismic
wave was input from the bottom of the foundation. The computation time step was 0.02 s, and the total time of computation was 16 s. The time history curve of the El Centro seismic wave is illustrated in Fig. 3.

Fig. 2 Mesh of model and key points

Fig. 3 Time history curve of El Centro seismic wave

3.2 Seismic stability safety analysis

In this study, with the restart function of the ADINA system, the numerical seismic analysis was carried out after the static analysis, which included the force of gravity on the rock (Bathe 1996; Singhal 1991). Considering that the whole seismic stability safety factor of the slope when it is subjected to earthquake loading may be less than 1, the strength reduction factors should also be less than 1 during the shear strength reduction method analysis, before the static and dynamic calculations are conducted. The dynamic horizontal displacement time history of the model subjected to earthquake loading was studied in order to analyze the dynamic response results and the stability of the gravity dam. The dynamic horizontal displacement time histories of several key locations were analyzed. The key points A and B are located at the crest and dam heel, respectively (Fig. 2). Fig. 4 and Fig. 5 show the dynamic horizontal displacement time histories of point A and point B, respectively, with different $K$ values.

Fig. 4 Dynamic horizontal displacement time histories of point A with different values of $K$
As shown in Fig. 4 and Fig. 5, when the $K$ value is small, the dynamic horizontal displacement time history curves of points $A$ and $B$ fluctuate around a certain value. When $K$ increases to a certain value between 1.136 and 1.203, the dynamic horizontal displacement time histories of points $A$ and $B$ will change. When $K$ further increases to 1.203, the dynamic horizontal displacement time histories of points $A$ and $B$ show a significant mutation that is unidirectional and irreversible. Meanwhile, the calculation does not converge. According to the analysis method of this study, the dam foundation is unstable when the $K$ value is between 1.136 and 1.203. Considering point $B$ the key point, the $K$-displacement curve of point $B$ is established (Fig. 6).

As shown in Fig. 6, when $K = 1.136$ under dynamic conditions, the permanent horizontal displacement of point $B$ jumps. Therefore, the seismic stability safety factor for this gravity dam is considered to be 1.136. The plastic zone distribution of the sliding surface when $K = 1.136$ is shown in Fig. 7, where the value of plastic flag indicates the strain conditions (When the value is equal to or less than 1, it represents elastic conditions; when the value is between 1 and 2, it represents the transition state from elastic to plastic; and when the value is greater than 2, it represents plastic conditions). Meanwhile, with the value changing from 1.125 to 3.825, the connectivity rate of the plastic zone is enhanced, and the failure regions of the element in
the slope are connected completely.

Fig. 8 shows the unstable shape at the end of the total computing time when \( K = 1.136 \). The shape vividly shows the critical state of the dam foundation. The value of \( K \) is the upper limit within which the foundation remains stable.

![Plastic zone distribution when \( K = 1.136 \)](image)

**Fig. 7** Plastic zone distribution when \( K = 1.136 \)

![Unstable shape when \( K = 1.136 \)](image)

**Fig. 8** Unstable shape when \( K = 1.136 \)

### 4 Conclusions

This study scientifically evaluated the seismic stability safety factor of slopes according to calculation results based on the FEM. It examined the physical mechanism of the inflection in the curve of the relation between the permanent horizontal displacements of key points and the values of \( K \). Based on this, the shear strength was reduced by different \( K \) values, and the static and dynamic analyses were conducted. When the calculation did not converge, the inflection appeared in the \( K \)-displacement curve, the failure region of the element in the slope connected completely, and the whole sliding channel was formed. The value of \( K \) was considered the seismic stability safety factor at this time. This method provides a new way to study seismic stability. The study of dynamic horizontal displacement time histories also provides a reference for further understanding of the failure mechanisms of rock slopes subjected to earthquake loading.
Convergence criteria should be selected according to practical problems. When the structure or component hardens, a minor structural deformation will introduce quite a large exterior load. Also, when the norm ratio of the displacement increment to the adjacent iteration jumps significantly, the convergent problem is thought of as non-convergent, in which case the displacement convergence criterion should not be considered. The convergence criterion should be selected properly, as it has significant influence on the calculation results. The displacement convergence criterion of the ADINA system was adopted in this paper. The comparative calculation shows that the results will be closer to reality when the displacement convergence criterion is applied to the ideal elastic-plastic problem.

In this study, the ideal elastic model was used to simulate the dam foundation and the Mohr-Coulomb criterion was used to study the sliding surface. It should be noted that the standard applied in this study for the minimum allowable seismic stability safety factor needs further research in order to make it consistent with related design safety standards, and the seepage impact on seismic stability should be considered in further seismic stability analysis studies.

References


