Stability analysis of concrete gravity dam on complicated foundation with multiple slide planes

Ren Xuhua*¹, Shu Jiaqing¹, Ben Nenghui², Ren Hongyun¹

1. College of Water Conservancy and Hydropower Engineering, Hohai University, Nanjing 210098, P. R. China 2. Shanghai Harbor Quality Control & Testing Co., Ltd., Shanghai 200032, P. R. China

Abstract: A key problem in gravity dam design is providing enough stability to prevent slide, and the difficulty increases if there are several weak structural planes in the dam foundation. Overload and material weakening were taken into account, and a finite difference strength reserve method with partial safety factors based on the reliability method was developed and used to study the anti-slide stability of a concrete gravity dam on a complicated foundation with multiple slide planes. Possible slide paths were obtained, and the stability of the foundation with possible failure planes was evaluated through analysis of the stress distribution characteristics. The results reveal the mechanism and process of sliding due to weak structural planes and their deformations, and provide a reference for anti-slide stability analysis of gravity dams in complicated geological conditions.

Key words: *multiple slide planes; anti-slide stability; mechanism of sliding; partial coefficient finite difference method*

DOI: 10.3882/j.issn.1674-2370.2008.03.007

1 Introduction

Anti-slide stability is always an important issue in gravity dam design, and it becomes the controlling factor if there are some weak structural planes in the dam foundation that may cause deep slide (Pan 1987). The slide mode of a gravity dam consists of shallow slide along the foundation base and deep slide in the foundation. Deep anti-slide stability is a more complicated problem than shallow anti-slide stability.

There are three kinds of weak structural planes: single, double and multiple slide planes (SETC 2000). The shear formulation is used to check the safety of single slide plane, and the stability analysis method suggested for double slide planes in the *Design Specifications for Concrete Gravity Dams* (SETC 2000) is the rigid block limit equilibrium method based on the double slide planes failure mode. But the distributions of stress and displacement cannot be obtained, and unreasonable results might arise in the anti-slide stability analysis of a complicated dam foundation using the limit equilibrium method because of too many assumptions (Tu et al. 2003). Chen and Chen (2002) and Cao et al. (2003) put forward some different opinions on the formula and parameters for deep anti-slide stability provided by the specifications according to their practical engineering experience. Huang and Nie (2005),

This work was supported by the Innovation Program for College Graduate of Jiangsu Province of 2007 (Grant No. CX07B_133Z).

^{*}Corresponding author (e-mail: *renxh@hhu.edu.cn*)

Received Feb. 28, 2008; accepted Aug. 7, 2008

Zhou et al. (2005) and Chang et al. (2007) have made further studies and investigations and offered their own ideas. But these studies are all based on the anti-slide stability of a wedge block with double inclined planes and no final conclusion has yet been achieved. The problem of multiple slide planes is more complicated than the others, so it is necessary to seek out the probable slide planes and instability forms and perform the stability analysis and safety evaluation of the dam with proper methods.

Using FLAC^{3D} software as the calculation core, the deep anti-slide stability of a hydroelectric station with multiple slide planes, located in the southwest of China, was investigated based on the strength reserve coefficient method with partial safety factors. The slide mechanism of the complicated foundation with weak structure planes was revealed through the strength reserve coefficient method, and the potential slide paths were obtained. In addition, the stability of the foundation with possible failure planes was investigated through analysis of the stress distribution characteristics, and then a comprehensive safety evaluation of the deep anti-slide stability of the project was made.

2 FLAC^{3D} finite difference software

The finite element method (FEM) is usually used for anti-slide stability analysis of a gravity dam, but it has some defects in solving large strain problems. Cundall has proposed fast Lagrangian analysis of continua (FLAC) based on the Lagrangian computation method in order to settle large strain and nonlinear problems, which FEM cannot solve easily. The principle of FLAC is similar to the discrete element method (DEM), but it can solve the continuous problems of irregular regions with different kinds of material modes and boundaries just like FEM. FLAC is also easy to run on a computer because it uses the dynamic relaxation method to avoid settling equation sets. Moreover, FLAC can solve the ordinary large strain problems and simulate the slide along the weak interface, and can reveal the plastic zone (Liu and Han 2005; ICG 1997). FLAC^{3D} software is therefore used as the calculation core, and, correspondingly, it is believed that the dam reaches its ultimate anti-slide bearing capacity and the plastic zone is regarded as the slide path of the dam when strength failure runs through the upstream and downstream slopes of the dam.

In the nonlinear analysis, the reasonable selection of constitutive equations and material parameters is one of the most important factors. The ideal elastoplasticity is used for the modeling (Sun and Zeng 2002) and the chosen yield criterion of the Drucker-Prager theory is as follows:

$$F = \alpha I_1 + \sqrt{J_2 - k_0} = 0 \tag{1}$$

where F is the yield criterion, I_1 is the first invariant of the stress tensor, J_2 is the second invariant of the deviatoric stress tensor, and α and k_0 are the positive constants defined as follows:

$$\alpha = \frac{2\sin\varphi}{\sqrt{3}(3-\sin\varphi)}, \qquad \qquad k_0 = \frac{6c\cos\varphi}{\sqrt{3}(3-\sin\varphi)}$$
(2)

where c is the cohesive strength and φ is the frictional angle of the material.

3 Methods of safety evaluation

There are several methods for safety evaluation of the dam. Two of them are used in this paper.

3.1 Stress analysis method

The safety factor is defined as the ratio of the sums of the anti-slide force and the slide force according to the distributions of normal stress and shear stress on the slide plane. The *Design Specifications for Concrete Gravity Dams* (SETC 2000) makes the following anti-slide stability requirement:

$$\gamma_{0}\phi S\left(\gamma_{G}G_{K},\gamma_{Q}Q_{K},\alpha_{K}\right) \leq \frac{1}{\gamma_{d1}}R\left(\frac{f_{K}}{\gamma_{m}},\alpha_{K}\right)$$
(3)

where *S* is the function of action effects; *R* is the function of structure resistance; $f_{\rm K}$, $G_{\rm K}$ and $Q_{\rm K}$ are, respectively, the characteristic values of material property, permanent load and variable load; $\gamma_{\rm m}$, $\gamma_{\rm G}$ and $\gamma_{\rm Q}$ are the corresponding partial safety factors of $f_{\rm K}$, $G_{\rm K}$ and $Q_{\rm K}$, respectively; γ_0 is the importance factor of the structure; $\gamma_{\rm d1}$ is the structural coefficient of fundamental combination; ϕ is the design situation factor; and $\alpha_{\rm K}$ is the characteristic value of the geometric parameter.

Parameter X is defined as follows:

$$X = S\left(\gamma_{\rm G}G_{\rm K}, \gamma_{\rm Q}Q_{\rm K}, \alpha_{\rm K}\right) / R\left(\frac{f_{\rm K}}{\gamma_{\rm m}}, \alpha_{\rm K}\right)$$
(4)

The nominal safety factor $X_{\rm K}$ can be expressed as

$$X_{\rm K} = \gamma_0 \phi \gamma_{\rm d1} S \left(\gamma_{\rm G} G_{\rm K}, \gamma_{\rm Q} Q_{\rm K}, \alpha_{\rm K} \right) / R \left(\frac{f_{\rm K}}{\gamma_{\rm m}}, \alpha_{\rm K} \right)$$
(5)

If $X \ge \gamma_0 \phi \gamma_{d1}$ or $X_K \ge 1.0$, the dam meets the anti-slide stability requirement.

3.2 Strength reserve coefficient method

If there are several weak structure planes or if the shape of the slide plane is undetermined in advance, the strength reserve coefficient method can be used. The ultimate strength reduction ratio is considered the safety factor (or called strength reserve coefficient k_u), and is obtained when the penetrating plastic zone appears and the structure is destabilized through the gradual reduction of the shear strengths of the soft interlayers and the supporting rock. The principle of the method is similar to the strength reduction FEM, which has been widely used in analysis of slope stability, but the method takes partial safety factors of materials and loads into consideration as required in the new *Design Specifications for* *Concrete Gravity Dams* (SETC 2000). The method can be called the partial safety factor numerical method. If k_{μ} is not less than X, the structure is safe.

4 Case Study

4.1 General situation of the project

The studied hydroelectric station is located in the southwest of China and has an installed capacity of 165 MW, a height of 60.2 m and a dam axis length of 300 m. The key structures are grade III according to the *Grade Division and Design Standard of Water Conservancy and Hydropower Projects*. The dam section with upper outlets is located on a major riverbed with complicated geological conditions and poor integrity. There are three argillaceous interlayers with low to moderate dip angles, J699, J771 and J782, and two low angle faults, f58 and f60. These weak structural planes cut each other and form disadvantageous combinations. The wedge block made up of J699, J782 and f60 is the probable slide block. Figure 1 shows the position of the argillaceous interlayers and faults in the dam foundation, and Figure 2 is a sketch map of a typical section.



Figure 1 Argillaceous interlayers and faults in the dam foundation



Figure 2 A typical section

4.2 Computation model and parameters

The numerical model shown in Figure 3 represents the dam section in the middle of the riverbed without taking the neighboring sections into account. A three-dimensional coordinate system is defined with the *x*-axis pointing downstream, the *y*-axis pointing from the right bank to the left bank and the *z*-axis pointing upward. The number of elements in the entire model is 26704 and the number of nodes is 41430.

Before the dam was built, initial stress existed in the bedrock. The initial stress is

composed of the tectonic and the gravity stresses. For simplification, the gravity stress is considered the initial stress because it is too complicated to simulate the tectonic stress and there are no measured results. Since the processes of dam body construction and water impoundment always have little influence on deformation and stress in the conventional operating mode, it is assumed that the dam body is poured entirely at one time and water impoundment is completed simultaneously.



Figure 3 FEM model

The necessary loads include dam gravity, upstream and downstream water pressures, uplifting pressure, wave pressure and silt pressure. When water levels were normal, upstream and downstream water heads were 47.0 m and 15.9 m, respectively, and upstream silt elevation was 30.0 m with a buoyant unit weight of 8 kN/m³. The physical and mechanical parameters of the materials of the dam body and the foundation are listed in Table 1.

Material	Bulk density (kN/m ³)	Young's modulus (GPa)	Poisson's ratio	Shear parameters	
				f'	<i>c</i> ′ (MPa)
Concrete	24.0	22.00	0.167		
Quartz sandstone	26.4	5.00	0.230	0.80	0.700
Charcoal sandstone	27.6	0.40	0.250	0.35	0.100
Sand sandstone	27.6	4.00	0.250	0.70	0.500
Fault	20.0	0.10	0.300	0.30	0.075
Argillaceous interlayer	10.0	0.02	0.300	0.20	0.010

Table 1 Physical and mechanical parameters of materials of dam body and foundation

4.3 Process analysis of failure

When the strength reduction ratio k is gradually increased from 1.0 to 1.11, partial failure appears and expands gradually, and then a penetrated slide plane forms and results in final failure of the dam foundation as shown in Figure 4, heavy lines indicating the plastic zone.

With the reduction of the parameters f' and c' of the dam foundation and argillaceous interlayers, the plastic failure appears in the three argillaceous interlayers. Then, the tensile-shear plastic failure appears at the dam heel and the compression-shear plastic

failure appears at the dam toe and fault f60 as shown in Figure 4(a). The tensile-shear plastic zone of the dam heel extends deep and upstream, and the compression-shear plastic zone of the dam toe extends downstream. With fault f60 extending deep along its strike, the argillaceous interlayers and f60 form the connected plastic zone as shown in Figure 4(b). Subsequently, the plastic zone appears in the dam foundation along the trend of the argillaceous interlayer and expands upstream, and all the plastic failure zones expand continuously (Figure 4(c)). Finally, all the plastic zones are connected along the dam foundation and the argillaceous interlayers (shown in Figure 4(d)) when the entire system reaches its ultimate bearing capacity.



Figure 4 Process of slide destruction of the dam foundation

4.4 Safety evaluation

4.4.1 Strength reserve coefficient method

The key structures are grade III, so the importance factor of the structure γ_0 is 0.9, the structural coefficient of fundamental combination γ_{d1} is 1.2, and the design situation factor ϕ is 1.0. The product of the three values is 1.08.

The calculation shows that when the plastic zones are connected along the dam foundation and the argillaceous interlayers, the value of k is 1.11. Therefore, the safety coefficient of this dam section is 1.11, which is obviously greater than the product of γ_0 , γ_{d1} and ϕ . According to the safety criterion proposed in this study, an optimistic estimation would conclude that this dam section meets the stability requirement and a conservative analysis would find that it is insufficiently safe.

4.4.2 Stress analysis method

The strength reserve coefficient method calculation shows that the final slide occurs along the dam foundation and the argillaceous interlayers. The stress analysis method is therefore used to check the stability of three possibilities: the dam foundation, the wedge block, and the combination of the dam foundation and the wedge block. Table 2 provides the calculation results.

In the table, $\sum W$ is the sum of the product of all the normal stress of the calculating face and its area, and *B* is the area of the calculating face. Similarly, $\sum P$ is the sum of the product of all the shear stress of the calculating face and its area. In order to fully take the effect of the cutoff wall into account, all the stress is decomposed and combined in $\sum W$ and $\sum P$.

Possibility	$f' \sum W$ (kN)	c'B (kN)	$\sum P(kN)$	X _K
Dam foundation	90 653.109	217 308.954	235 451.960	1.211
Wedge block	3 693.214	26 702.899	35 446.535	0.794
Combination of dam foundation and wedge block	81 257.080	171 575.540	233 171.600	1.004

Table 2 Computation of three possibilities

According to this calculation, the dam foundation meets the stability requirement. The combination of the dam foundation and the wedge block basically meets the stability requirement as well, but the wedge block needs reinforcement because its nominal safety factor is less than 1.0, so the anti-slide stability of the wedge block is of importance to the deep anti-stability of the project.

5 Conclusions

The following conclusions can be drawn:

(1) The strength reserve coefficient method with partial safety factors is essentially based on the reliability method. It deals with the basic factors influencing the anti-slide stability in advance through partial safety factors. Taking overload and material weakening into consideration, it matches the methods in current specifications, and is more scientific and rational than the traditional safety coefficient method and strength reduction FEM.

(2) The failure of a dam is very complicated under complex geological conditions with multiple slide planes. The probable forms of slide planes are uncertain. This study used the strength reserve coefficient method with partial safety factors to analyze the anti-slide stability of a dam with a complicated foundation, and the probable forms and safety factor of slide planes were obtained. The results conform to the actual situation on the whole, which demonstrates that the method is effective in the stability analysis and safety evaluation of a gravity dam on a complicated foundation with multiple slide planes.

References

Cao, Q. X., Bai, B. Z., and Wang, G. M. 2003. Discussion of the limit states design equation of anti-slide stability of the gravity dam. *Yangtze River*, 34(7), 40-42. (in Chinese)

Chang, X. L., Huang, D. J., Jiang, C. Y., and Cao, Q. X. 2007. Research on expression and partial coefficients

of anti-sliding stability of gravity dams. *Chinese Journal of Geotechnical Engineering*, 29(8), 1219-1223. (in Chinese)

- Chen, Z. Y., and Chen, L. H. 2002. Discussions on the wedge stability analysis method specified in the Gravity Dam Design Code. *Journal of Hydroelectric Engineering*, 21(2), 101-108. (in Chinese)
- Huang, D. J., and Nie, G. M. 2005. Research on several problems in the safety evaluation of stability against deep slide of gravity dams-in response to the "discussion of the wedge stability analysis method specified in the Gravity Dam Design Code". *Journal of Hydroelectric Engineering*, 24(2), 90-94. (in Chinese)
- Itasca Consulting Group, Inc. (ICG). 1997. Fast Language Analysis of Continua in Three Dimensions. Minneapolis: Itasca Consulting Group, Inc.
- Liu, B., and Han, Y. H. 2005. *Principle, Example and Application Guide of FLAC*. Beijing: China Communications Press. (in Chinese)
- Pan, J. Z. 1987. Design of Gravity Dam. Beijing: Water Resources and Electric Power Press. (in Chinese)
- Sun, G. R., and Zeng, X. H. 2002. Parameter value and safety storing for finite element method analysis of gravity dam. *Design of Hydroelectric Power Station*, 18(2), 25-30. (in Chinese)
- The State Economic and Trade Commission, P. R. China (SETC). 2000. *Design Specifications for Concrete Gravity Dams (DL5108-1999)*. Beijing: China Electric Power Press. (in Chinese)
- Tu, J., Zhou, L. B., Li, D. Y., and Hou, S. Z. 2003. Study on stability against sliding at deep level of foundation in gravity dam. *Journal of Hydraulic Engineering*, 34(10), 96-100. (in Chinese)
- Zhou, W., Chang, X. L., and Yuan, L. J. 2005. Supplementary discussion on the double-inclined wedge stability analysis method specified in the Design Specifications for Concrete Gravity Dams. *Journal of Hydroelectric Engineering*, 24(2), 95-99. (in Chinese)