STATIC AND DYNAMIC ANALYSIS ON THE GRAVITY DAM ANTI-SLIDING STABILITY UNDER UNITED FORM BETWEEN DAM AND PLANT

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ABSTRACT:

In this paper, the deep and shallow anti-sliding stability of gravity dam under united form between dam and plant is analyzed in Jin'anqiao hydropower plant sect, through the method of limit equilibrium and strength accumulation coefficient method. Based on the geological data, from which the left plane in double-inclined slide mode can be ascertained, a function is educed between structure coefficient and obliquity of the right plane in the double-inclined slide mode; then the worst anti-sliding structure coefficient can be known. At the same time, strength accumulation coefficient method is adopted for safety checking. The results of the both methods show, for the Jin'anqiao hydropower riverbed dam sect, the deep and shallow anti-sliding stability can be ensured, and the united form can well improve anti-sliding stability of the dam bedrock.

KEYWORDS: gravity dam, united form between plant and dam, anti-sliding stability, limit equilibrium method, strength accumulation coefficient method

1. INTRODUCTION

Anti-sliding stability of gravity dams is a key factor that affects the safety of dams, enough attention should be paid. For the scheme of plant behind the dam, when the project has overfall across the top of plant、high downstream water level, or a high demand of anti-sliding stability of the dam, plant and dam usually are designed as a union, such as Wujiangdu, Manwan, Yantan and so on. HUANG,A.L(1995) explained the advantage of plant-dam union through the change of displacement of key points. REN.Q.W et al(1999) simply explained the effect of the plant-dam union using limit equilibrium and block finite element method. DONG.Y.X et al(2001) studied the mechanical property of super size penstocks, and found that the union can improve the loading condition of the penstocks. YU.W.P et al(2006) studied displacement of key points at dam-heel and foundation plane of plant, made a similar conclusion that the dam-plant union can improve the anti-sliding stability of dam on the river.

Jin'anqiao hydropower engineer plant sect was studied as a case in this paper. In the analysis of rigid body limit equilibrium method, the left plane in double-inclined slide mode was ascertained in term of the geological data, a function is educed between structure coefficient and obliquity of the right plane, and then the worst anti-sliding structure coefficient can be known. At the same time, strength accumulation coefficient method is adopted for safety checking in order to study the influence of the united form on anti-sliding.

2. COMPUTATIONAL METHOD OF ANTI-SLIDING STABILITY

2.1. Rigid Body Limit Equilibrium Method

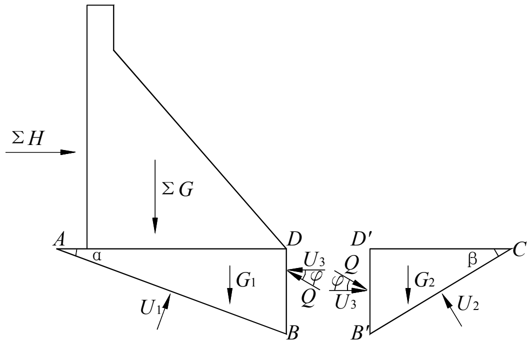

Figure 1 Sketch of double-inclined slide mode

Double-inclined slide mode is show in Fig.1, the formula for checking the structure carrying capacity in present code (DL5108-1999) is expressed as:

$$\gamma_o \varphi S(\gamma_G G_K, \gamma_Q G_Q, a_K) \le \frac{1}{\gamma_d} R(\frac{f_K}{\gamma_m}, a_K) \tag{1.1}$$

The formula in the code has some irrational aspects (CHEN 2002). Using the rigid body limit equilibrium method, ZHOU.W et al (2005) obtained the anti-sliding stability of gravity dams, equation of calculation the credibility on the limit condition, educed the relationship between the resist force and effect function, this method can avoid the irrational aspects in the code. The resist force and effect function on the slide surface AB can be expressed as:

$$R(\bullet) = f'_{d1}\left[(\sum W + G_1)\cos\alpha - \sum H \sin\alpha - Q\sin(\varphi - \alpha) + U_3 \sin\alpha - U_1\right] + c'_{d1} A_1 \tag{1.2}$$

Where

$$Q = \frac{f'_{d2}(G_2 \cos\beta + U_3 \sin\beta - U_2) + G_2 \sin\beta - U_3 \cos\beta + c'_{d2} A_2}{\cos(\varphi + \beta) - f'_{d2} \sin(\varphi + \beta)} \tag{1.3}$$

Effect function: $S(\bullet) = \left(\sum W + G_1\right)\sin\alpha + (\sum H - U_3)\cos\alpha - Q\cos(\alpha - \varphi)$ (1.4)

The sense of the symbols in the function coincides with the code (DL5108-1999) and where the angle φ in Figure 1 is set to 0 safely.

Let $$\gamma_d{}' = \frac{R(\bullet)}{\gamma_o \varphi S(\bullet)} \tag{1.5}$$

Then formula (1.1) can be expressed as: $\gamma_d \le \gamma_d{}'$. (1.6)

Angle β of right slide surface BC in Eqn. (1.5) is unknown; using the formula $\gamma_d{}' = \gamma'_d(\beta)$ the most dangerous angle β can be calculated:

$$\frac{\partial \gamma'_d}{\partial \beta} = \frac{\partial}{\partial \beta}(\frac{R(\bullet)}{\gamma_o \varphi S(\bullet)}) = 0 \tag{1.7}$$

Then the γ_d' can be obtained, using the formula (1.6) to check the anti-sliding stability.

2.2. Strength Accumulation Coefficient Method

Strength accumulation coefficient method is a limit equilibrium analysis method based on the safety factor definition. The material property of the dam foundation varies great and can't be ascertained well, even sometimes lowers than the standard value. Strength accumulation coefficient method is proposed to consider this uncertainty for check the structural safety factor, this method successively reduce the structural strength parameters k and c for K_f times, using the new strength parameters to carry nonlinear finite element analysis until the structure into the critical situation of structure failure, then the K_f is the strength accumulation coefficient of the material. The yielded surface of the material on the sliding surface is the inscribed circle yielded rule, more can see the literature (DU 2002)

The criterions of judging the structure failure (CHANG 1996) are: yielding transfixion rate of slide surface; the displacement of key point changes abruptly; the computational result does not convergence. Usually portion or all of above criterions are used to judge the structural failure.

3. JIN'ANQIAO GRAVITY DAM ENGINEERING GEOLOGY AND POTENTIAL SLIDE WAY ANALYSIS

Jin'anqiao gravity dam locate on middle reaches of Jinsha river, and the dam is a roller compacted concrete gravity dam, with the bottom of the dam at elevation 1 264m and the top 1 424m. The plant is lay behind the dam. Materials of the foundation are mainly compact basalt, almond basalt, volcano gravel with two tuff interlayers t_{1b} and t_{2b}. t_{1b}, below foundation plane about 20m, will affect the deep anti-sliding stability of the dam. And there are many interfaces filled with chloritization rock on the riverbed, which has little volume, lower resist shear strength and deformation capability, which goes against the anti-slide stability of dam foundation. In addition, the seismic fortification intensity reaches to 9 degree (i.e. earthquake peak acceleration 0.3995g), so it is very important to evaluate the anti-sliding stability of the JIN'ANQIAO RRC gravity dam. Fig.2 shows the section plane of the dam.

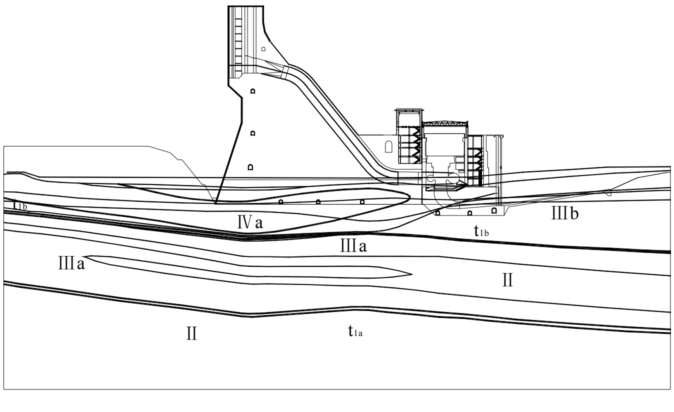

Figure 2 Cross section of Jin'anqiao plant sect

3.1. Sliding Paths

Plant sect is the closest to the interlayer t_{1b}, and has shallow distribution of chloritization rock below, so the stability mode of the dam may be:

Slide mode 1: The left sliding plane lies in the crack plane with severe chloritization rock under foundation plane, and right one shears out from Ⅳa rock.

Slide mode 2: Take the interlay t_{1b} as the left sliding plane and right sliding plane is sheared out from Ⅳa rock at plant end.

Slide mode 3, 4, 5: Take the interlay t_{1b} as the left sliding plane. But the right sliding plane is consist of the interface between severe chloritization rock and normal chloritization normal rock, as well as fold line of chloritization rock and foundation plane of plant. The shear-out point lies at the end of plant.

It is analyzed through limit equilibrium method in sliding mode 1 and 2, while 2D and 3D finite element method is adopted in sliding mode 3, 4 and 5. The form of sliding mode 1 and 2 is shown in Fig.3, and that of sliding mode 3, 4 and 5 is shown in Fig.4.

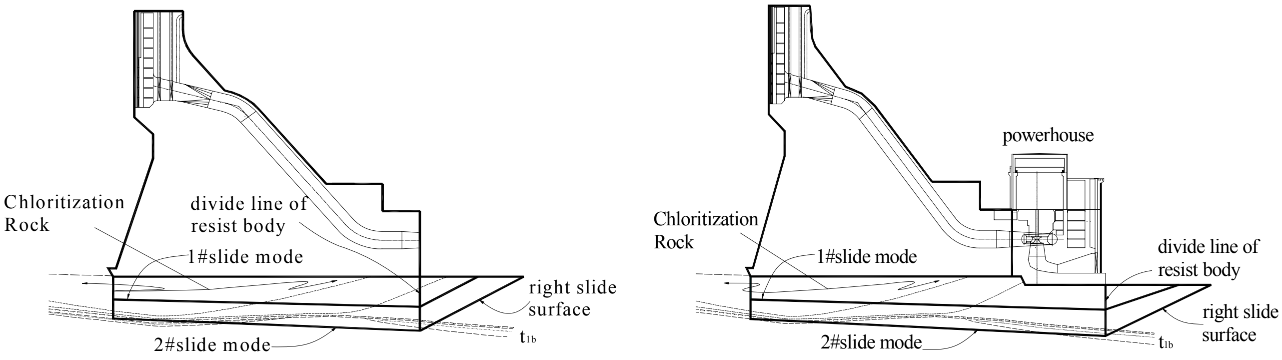

Figure 3 Slide modes of dam bedrock under both forms between dam and plant

3.2. Calculation Cases and Related Parameters

Load condition under various cases is given in Table 3.1, where dynamic analysis is applied to seismic load based on the mode decomposition response spectrum method and response spectrum uses the standard one recommended by 《specifications for seismic design of hydraulic structures》(DL5073-2000) with the maximal spectrum value β_{max}=2.0 and site eigenperiod T_g=0.2s . Considering the first ten-order vibration modes, it is calculated for horizontal seismic action by the type of SRSS. Vertical seismic load and horizontal one pointing to downstream face is being the adverse case, which is superposed with normal load case to complete anti-sliding stability analysis. The physical-mechanical parameters of dam concrete and the dam foundation are given in Table 3.2.

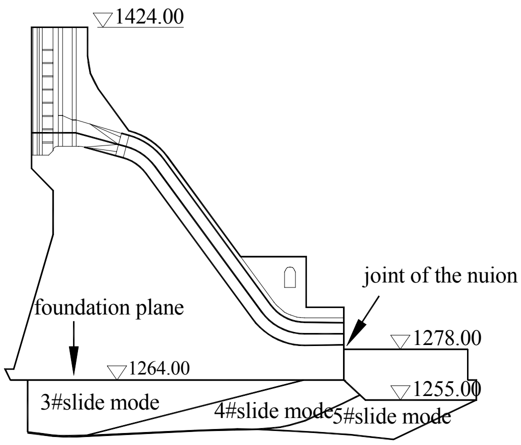

Figure 4 Slide modes of bedrock of the riverbed dam sect

Table 3.1 Analysis Loadcase

Upstream waterlevel/m	Downstream waterlevel/m	Loadcases
1418.000	1293.899	Deadweight＋upstream and downstream water pressure＋uplift pressure＋silt pressure
1421.000	1321.744	Deadweight＋upstream and downstream water pressure＋uplift pressure＋silt pressure
1418.000	1293.899	Normal case load＋seismic load

4 INTRODUCTION FOR CACULATION MODEL

2D and 3D finite element model is established in order to detail the united action between dam and plant, in which various kinds of rock and tuff t_{1a} and t_{1b} are simulated. Foundation depth is 3 times the height of dam, and extends horizontally 3 times the height from dam heel to upstream side and from dam toe to downstream side respectively. 3D model only simulated 34m wide of single dam sect along lengthwise direction of the dam. Boundary of bedrock is applied to normal restriction.

Plane finite element model adopted 8-node isoparametric element, and 6-node triangular element, in which the number of elements and nodes is 2019 and 6309 respectively. 8-node hexahedral element is used in the 3D model with 31438 elements and 36941 nodes. Plane finite element model is displayed in Fig.5.

Table 3.2 Physical-mechanical parameters

Category	Density ρ / ($t{\cdot}m^{-3}$)	Elastic module E/GPa	Poisson's ratio μ	f	Cohesive strength /MPa
Dam body	2.4	22	0.167	1.1	2.0
United joint between dam and plant	2.4	22	0.167	/	/
Foundation plane	2.4	20	0.167	0.95	0.70
Rock II	2.6	18	0.25	1.40	1.80
Rock IIIa	2.7	12	0.26	1.35	1.30
Rock IIIb	2.6	10	0.27	1.15	1.00
Rock IVa	2.5	9	0.28	0.95	0.70
T_{1b}	2.3	2	0.28	0.725	0.40

Initial stress has existed in the bedrock before building the dam, which is composed of tectonic stress and self-weight stress of rock. Because sliding surface is not so deep to foundation plane, stress field of self-weight stress of rock can well simulate the initial stress. Elastic-plastic finite element analysis is employed in calculation process.

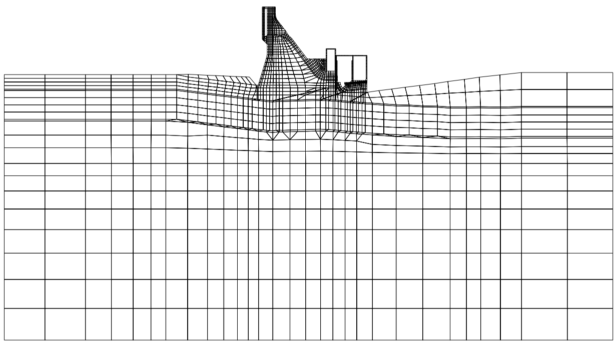

Figure 5 2D FEM mesh of gravity dam and base

In the united form, grouting elevation is selected as 1278m, which is 2 m below diversion steel pipe at the joint. The upward is almost beam, plate or column, which has little influence on anti-sliding stability of the dam, but can increase stress of plant. The joint elevation begins from foundation plane when there is no grouting.

5 RESULTS ANALYSIS

5.1. Results Based on the Limit Equilibrium Method of Rigid Body

Through analysis of the limit equilibrium method, anti-sliding stability is accounted along foundation plane and sliding mode 1、2 in both forms between dam and plant. Stability result is collected in Table 5.1. And the angle β is determined by Eqn. (1.7) under normal pool level condition. In the form of dam-plant separated, β is respectively 24.8°, 27.8° in mode 1 and mode 2; while In the form of dam-plant united, β is respectively 19.78°、23.1°. As seen in table 5.1, anti-sliding stability structure coefficient of normal case and checking case is more than 1.2, earthquake case more than 0.65. All the 3 cases meets code request. Anti-sliding structure coefficient in the earthquake case is minimum and is the control case of the deep and shallow anti-sliding stability. From the table we also can see that, in all the 3 cases, anti-sliding stability structure coefficients in the united form are greater than those when dam and plant are separated; the united form can improve anti-sliding stability of dam and plant very well; in other word, redundant safety of anti-sliding stability is higher.

Table 5.1 Anti-sliding results of bedrock

Sliding mode	Calculation cases	Separated form			United form		
		Effect $\gamma_0\varphi S(\cdot)$ /kN	Resistance $R(\cdot)\gamma_d^{-1}$ /kN	Anti-calculation structure coefficient γ_d	Effect $\gamma_0\varphi S(\cdot)$ /kN	Resistance $R(\cdot)\gamma_d^{-1}$ /kN	Anti-calculation structure coefficient γ_d
Foundation plane	Normal case	135 935.5	219 762.39	1.94	135 935.5	231 889.0	2.05
	Checking case	109 629.4	184 542.82	2.02	109 629.4	211 874.0	2.32
	seismic	206 961.12	305 665.65	0.96	221 579.2	357 519.05	1.04
Mode 1	Normal cases	146 353.40	150 500.20	1.23	146 484.30	159 912.03	1.31
	Checking case	145 543.61	155 245.20	1.28	144 155.33	160 973.45	1.34
	seismic	242 540.44	250 003.22	0.67	255 747.49	302 962.41	0.77
Mode 2	Normal cases	161 629.32	176 445.34	1.31	160 997.70	181 122.41	1.35
	Checking case	144 985.27	193 313.69	1.60	145 041.20	219 979.15	1.82
	Seismic case	254 334.02	258 246.85	0.66	268 889.94	310 257.62	0.75

structure significance coefficient $\gamma_0 = 1.1$,design condition coefficient $\varphi = 1.0$，0.95，0.85, corresponding to normal case, checking case and earthquake case.

Table 5.2 Yielding transfixion rate of sliding modes of different K_f

Grouting Elevation	Sliding mode	2D				3D			
		K_f=2.5	K_f=3.0	K_f=3.5	K_f=4.0	K_f=2.5	K_f=3.0	K_f=3.5	K_f=4.0
No grouting	Foundation plane	0.890	0.931			0.885	0.917		
	3#	0.481	0.729			0.554	0.641		
	4#	0.733	0.760			0.879	0.886		
	5#	0.781	0.860			0.901	0.911		
Grouting Elevation 1278m	Dam foundation			0.760	0.870			0.813	0.885
	3#		0.483	0.771	0.865		0.541	0.792	0.866
	4#		0.774	0.821	0.853		0.886	0.903	0.903
	5#		0.732	0.845	0.885		0.895	0.950	0.950

5.2. Results Based on the Strength Accumulation Method

Table 5.2 is yielding transfixion rate of different sliding modes using 2D and 3D finite element models in the different strength accumulation coefficients.

Seen from plane results in Table5.2, strength accumulation coefficient K_f may be up to 2.5～3.0 without grouting between dam and plant. Among them max yielding transfixion rate of different sliding modes on the sliding surface is 0.89 along foundation plane. When K_f is 3.0, max yielding transfixion rate is also on the datum plane and that of sliding mode 5 is second greatest. When strength accumulation coefficient K_f is 3.5 in the united form, max yielding transfixion rate is 0.845 in the sliding model 5, but there is still some storage room. Compared with yielding transfixion rates of different K_f in different sliding paths, whether dam and plant is united or separated, both yielding transfixion rates of foundation plane and sliding mode 5 is higher than those of the others. In other word, mechanical property of foundation plane and t_{1b} has great influence on anti-sliding stability of the dam block.

Table 5.2 presents the results of 3-D finite element model. Compared the result with that of plane, yielding transfixion rate in 3-D finite element model is greater than that in plane one, for the same K_f and the same sliding mode. This is mainly because 2-D model is not better than 3-D model in simulation of dam and foundation. In addition Table 5.2 also shows that, strength accumulation coefficient is 2.5～3.0 under dam-plant separated; strength accumulation coefficient may be up to 3.5 if dam and plant are united, and yielding transfixion rate of foundation plane and sliding mode 5 is greater than the other two sliding paths which is consistent with plane results.

6 CONCLUSION

The following conclusion can be drawn as:

a. Through the method of limit equilibrium, in RCC gravity dam and plant in Jin'anqiao, the deep and shallow anti-sliding stability structure coefficient under the static load is more than 1.2, that under the earthquake load is smaller and more than 0.65, which meets the code requirement. Among them earthquake case is the control case of anti-sliding stability.

b. Observed from the results of strength accumulation coefficient, mechanical property of foundation plane and t_{1b} has great influence on anti-sliding stability safety of the dam sect. Strength accumulation coefficient of material is 2.5～3.0 if dam and plant are separated, that may be up to 3.0～3.5 if dam and plant are united, which can guarantee anti-sliding stability safety of the dam sect fully.

c. Adopting united form between dam and plant, the anti-stability in Jin'anqiao hydropower plant sect will be improved obviously.

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