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Researches on deposit slope stability against sliding: a case study

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Researches on deposit slope stability against sliding: a case study

Osias Ndayirukiye[1], Zhanrong Lu[1], Mingxun Hou[1, *], Zhenjun Wu[2]

[1]School of Architecture Ocean and Civil Engineering, Shanghai Jiao Tong University, Shanghai 200240, China
[2]Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Wuhan 430071, China

*Corresponding author e-mail: 45184737@qq.com

Abstract. The stability of deposit slopes against sliding is studied using the limit equilibrium methods in this paper. As a case study, all the results are shown based on deposit slope in front of the dam of A'hai Hydropower Station, China. A calculating strategy to improve the convergence of rigorous Janbu method is proposed using cubic B-spline interpolation smoothing processes of inter-slice moment distribution. The factor of safety calculated by the modified rigorous Janbu method in this paper is consistent with those obtained by other limit equilibrium methods. It has been shown that the deposit slope in front of the dam is stable under natural conditions. The factor of safety of deposit slope stability against sliding is between 0.865 and 1.167 under normal water level conditions, which indicates that local instability of deposit exists. The factor of safety is sensitive to internal friction angle of alluvium under the water-saturated state. Some treatment measures are briefly discussed to improve the stability of the deposit in front of the dam.

1. Introduction

It is well known that slope stability against sliding is evaluated by using the factor of safety, which is one of the most important concepts in slope stability analyses. The definition of the factor of safety is the ratio of the shear strength of rock and soil to shear stress required for equilibrium in geotechnical engineering. An alternative way to state this definition is that the factor of safety is the factor by which the shear strength of rock and soil materials would have to be divided to bring the slope into a state of barely stable equilibrium [1]. In determining the factor of safety in slope stability analyses, there are many available approaches that can be used, such as the limit equilibrium analysis [1], block theory [2], distinct-element method [3], finite element method (FEM) [4], and the vector sum method [5-7]. Among these methods, the limit equilibrium analysis method seems to be the most popular one, the reason being that it has some particular advantages [8]. According to different assumptions on the calculation of inter-slice forces, the limit equilibrium method can be divided into several classifications such as Swedish method [9], Bishop Method [10], Spencer method [11,12], Morgenstern-Price method [13] and Janbu method [14]. It has been shown that the non-convergence of the rigorous Janbu method inherently in its original solution process can be eliminated by using smooth inter-slice moment distribution prescribed at specific locations within the sliding body, leading to stable convergence [15]. In this research, the limit equilibrium method is used to study the stability of large-scale deposit slope in front of the dam of A'hai Hydropower Station, China.

In this paper, the engineering geology problems at the dam area of A'hai Hydropower Station, China, are analyzed. Then the cubic B-spline interpolation smoothing processes of inter-slice moment distribution of the rigorous Janbu method is researched. In the following, the global and local factors of safety of deposit in front of the dam are calculated. The stabilities of deposit in front of the dam is also evaluated. Finally, some engineering treatment measures of deposit slope instabilities are also discussed in brief.

2. Overview of engineering geology in the dam area

A'Hai hydropower station is located on Jinsha River in Yulong county (right bank) and Ninglang county (left bank) of Lijiang city, Yunnan province, China. It is the fourth level of eight cascade hydropower stations in the midstream of the Jinsha River. Electric power generation is the main function of the A'Hai hydropower station with an installed capacity of 2000MW. The dam is a roller compacted concrete gravity dam with a maximum height of 138m and a normal water level of 1504m [16].

The Jinsha River flows from north to south within the dam areas. The natural topography of bank slopes has their dip angles of 35°-45°. The gullies on both bank slopes are developed, and the valley is of "V" type at the dam site. Therefore, the geological structures are complicated in the engineering areas. The basic earthquake intensity is at level VIII on site of A'Hai hydropower station. The landslides and deposit bodies have the potential threats to the stability of reservoir banks. There are three main deposit slopes in the engineering areas of A'hai Hydropower Station, namely the deposit slope in front of the dam, Donglian and Kuzhi deposit slope near the dam. Among these deposit slopes, the large-scale deposit slope of the left bank in front of the dam has a significant influence on the stability of the reservoir bank. In this research, the stability analyses of the deposit slope in front of the dam are performed as an example. The plane diagram of the deposit slope in front of the dam is shown in Fig. 1. There are eight controlling sections marked by B1, B2, B3, B4, B5, B6, B7, B8 respectively.

The deposit slope in front of the dam is located on the left bank of the upper Jinsha River, about 300m from the dam axis. The elevation of the leading edge of the deposit is generally 1450m-1460m, that of the trailing edge is about 1620m. It is about 800m in length along the river and 300m-380m in width in the direction of cross-river. The volume of the deposit is about 4.7 million m^3, and the deposit has slope geomorphology with a dip of 30°-45°. The topography in the leading edge of the deposit is steep, while there are some gentle slope terrains in the trailing edge of the deposit, whose elevation is about 1600m. According to geological survey and engineering borehole explorations, the deposit slope is formed by Quaternary alluvial, slope deposit, avalanche, moraine and so on. The width is about 20m-45m in the middle and front of the deposit slope. The maximum width explored by a geological borehole is 47.32m. In the rear and front sides of the deposit slope, the thickness is relatively less.

The geological section of B6 is shown in Fig. 2. The deposit slope is mainly composed of the lower alluvium of the ancient riverbed and the upper moraine. For the lower part, it consists of sand gravel, boulders, and silty sand. The deposits are characterized by near-horizontal stratification and rhythm, whose thickness is 15m-40m. The upper moraine consists of fragmented stones, but they have good compactness. There exists phreatic water in upper deposit slope. The alluvium is sandwiched with fine silty sand layers distributed horizontally in the flow direction of the river. The elevation ranges from 1460 m to 1470 m. The total length of fine silty sand layers is 380m. The silty sand layer is slightly cemented when it is dried, but it will still appear granular when it is exposed to water. Compared with the other rock and soil layers in the deposit slope, the engineering properties of the silty sand layer are relatively weak. Therefore, there is possibility of potential slip and instability along the silty sand layer. The underlying bedrock of deposit in front of the dam is mainly made up of diabase and Devonian metamorphic rocks. Most of the underlying bedrock is weakly weathered, while a small number of the rock mass is strongly weathered. The structural planes in bedrock are bedding surfaces, whose strike has a larger angle relative to valley direction. The underlying bedrock surface is a curved interface inclined to the river bed.

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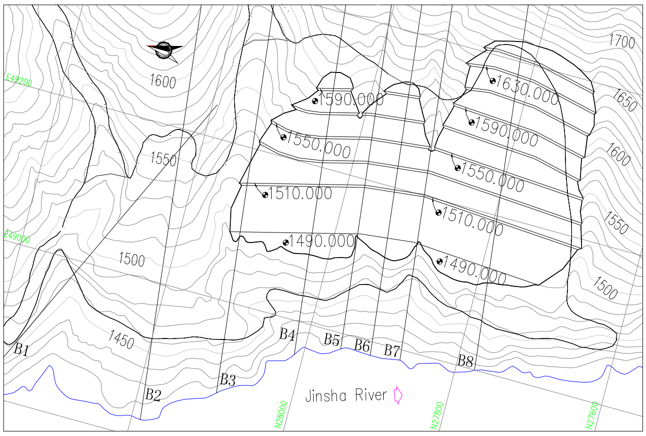

Figure 1. The plane diagram of the deposit slope in front of the dam of A'Hai hydropower station

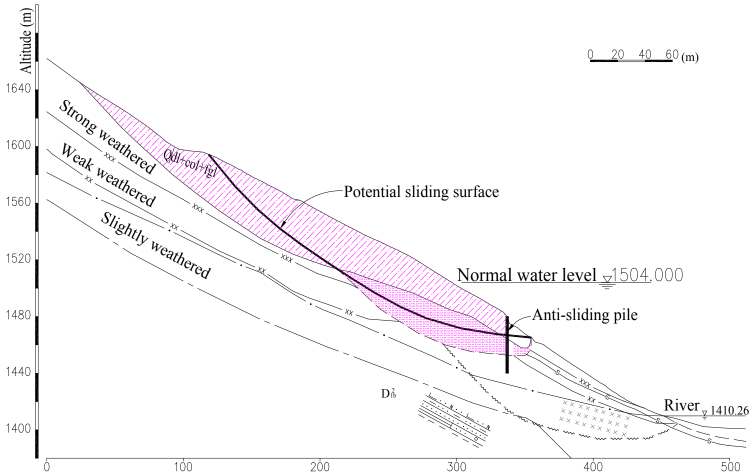

Figure 2. The geological structures for section B6 of the deposit slope

3. Stability analysis of the deposit slope in front of the dam

3.1. Modification to rigorous Janbu method

The limit equilibrium method is used to study the stability of the deposit slope in front of the dam. As mentioned in the previous sections, the rigorous Janbu method has its disadvantage of non-convergence in obtaining the factor of safety. In order to overcome this non-convergence of rigorous Janbu method, the cubic B-spline interpolation smoothing processes of inter-slice moment distribution is deduced in this section. The Janbu method assumes the position of the inter-slice force, that is, the thrust line position, which fully satisfies the force and moment balance conditions. Moreover, the modified Janbu method can be used to obtain the factor of safety of slope stability for a slope with an arbitrary slip surface. It has been shown that the stable convergence can be achieved by setting the thrust line position and utilizing the smooth inter-slice moment distribution [15]. The force diagram of a typical slice for rigorous Janbu method is demonstrated in Fig. 3. For the improved rigorous Janbu method, the factor of safety of slope stability can be calculated according to the following formula [15]

$$F_S = \frac{\sum_{i=1}^{n-1}\left(R_i \cdot \prod_{k=i+1}^{n} \psi_k\right) + R_n - E_1 \prod_{j=1}^{n} \psi_j + E_{n+1}}{\sum_{i=1}^{n-1}\left(T_i \cdot \prod_{k=i+1}^{n} \psi_k\right) + T_n} \tag{1}$$

Where,

$$\psi_i = \frac{(\sin\alpha_1 - f_i\cos\alpha_i)\tan\varphi_i^{'} + (\cos\alpha_i - f_i\sin\alpha_i)F_S}{(\sin\alpha_i - f_{i+1}\cos\alpha_i)\tan\varphi_i^{'} + (\cos\alpha_i + f_{i+1}\sin\alpha_i)F_S} \tag{1a}$$

$$T_i = \frac{(W_i + M_i^{'} - M_{i+1}^{'} + t_i - t_{i+1})\sin\alpha_i + K_c W_i\cos\alpha_i}{(\sin\alpha_i - f_{i+1}\cos\alpha_i)\tan\varphi_i^{'} + (\cos\alpha_i + f_{i+1}\sin\alpha_i)F_S} \tag{1b}$$

$$R_i = \frac{(W_i + M_{i+1}^{'} + t_i - t_{i+1})\cos\alpha_1\tan\varphi_i^{'} - (K_c W_i\sin\alpha_i + U_i)\tan\varphi_i^{'} + c_i^{i} l_i}{(\sin\alpha_i - f_{i+1}\cos\alpha_i)\tan\varphi_i + (\cos\alpha_i + f_{i+1}\sin\alpha_i)F_S} \tag{1c}$$

$$E_{i+1} = \psi_i E_i + F_S T_i - R_i \tag{1d}$$

The meaning of each symbol in equation (1) can be referred to [15]. According to the equation (1), the first-order derivative of the inter-slice moment is involved in the process of solving the factor of safety by an iterative method. In this paper, the cubic B-spline interpolation function is used to fit the inter-slice moment to make sure that its first-order derivative is continuous and derivable. As a result, the convergence for calculating the factor of safety can be greatly improved.

A schematic of a sliding body, the position of the assumed inter-slice force action points, and the thrust line is shown in Fig.4. The calculation process of approximating the inter-slice moment using the cubic B-spline interpolation function is briefly summarized as follows.

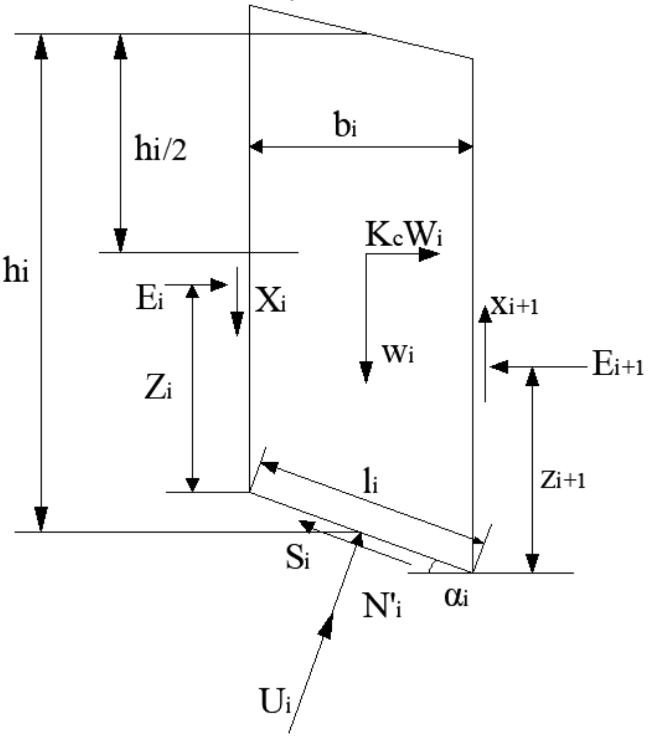

Figure 3. The force diagrams of a typical slice for rigorous Janbu method

For division $\triangle$ of arbitrary interval $[a, b]$, m degree spline function $s(x) \in S(m,\triangle)$ can be expressed as

$$S(x) = \sum_{j=-m}^{n-1} a_j B_{j,m}(x) \tag{2}$$

The cubic B-spline interpolation function $S(x)$ is used to approach the inter-slice moment M. Firstly, the sliding line is evenly divided into 4 segments along its length direction, thus 5 interpolating points x_0, x_1, x_2, x_3, x_4 are obtained. The values of inter-slice moment M at the corresponding interpolation points are noted by f_0, f_1, f_2, f_3, f_4, respectively, and their derivative values noted by $f_0', f_1', f_2', f_3', f_4'$. Then the following equations can be obtained [16]

$$\begin{cases} \sum_{j=-3}^{3} a_j B'_{j,3}(x_0) = f_0 \\ \sum_{j=-3}^{3} a_j B_{j,3}(x_i) = f_i, i = 0,1,4 \\ \sum_{j=-3}^{3} a_j B'_{j,3}(x_4) = f'_4 \end{cases} \tag{3}$$

where $B_{j,3}$ is the cubic B-spline basis function, $B'_{j,3}$ is the derivative of the cubic B-spline basis function. In this way, the problem of finding $S(x)$ in equation (2) is transformed into solving the coefficients $a_{-3},...,a_0...a_3$, which is to solve linear equations. After obtaining these seven coefficients $a_{-3},...,a_0,...,a_3$, the first derivative of $S(x)$ can be expressed as

$$S'(x) = \sum_{j=-3}^{n-1} a_j B'_{j,3} = \sum_{j=-3}^{3} 3a_j \left[\frac{B'_{j,2}(x)}{x_{j+3} - x_j} - \frac{B'_{j,2}(x)}{x_{j+4} - x_{j+1}} \right] \tag{4}$$

According to equation (4), $(M'_i - M'_{i+1})$ can be calculated. Then the factor of safety F_s can be found through iterative scheme based on equation (1).

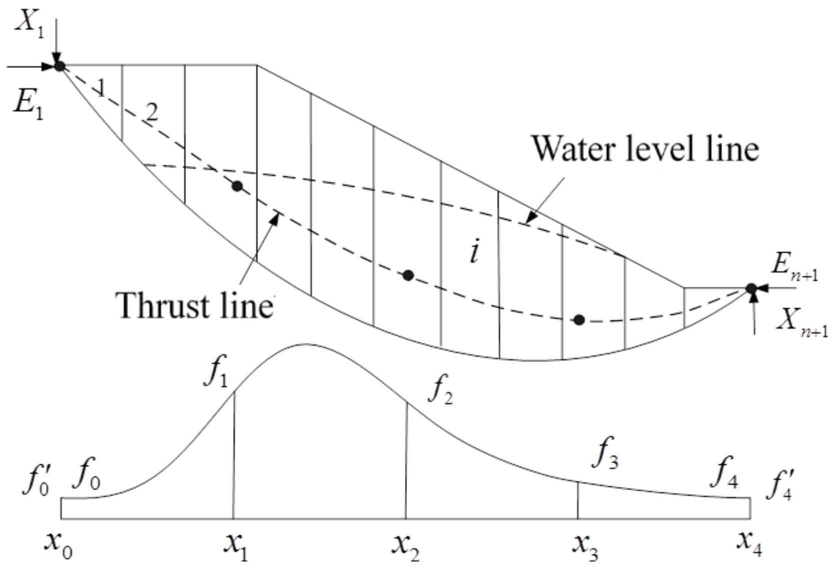

Figure 4. Inter-slice moment approximated by a cubic B-spline function

3.2. Stability analysis of deposit slope in front of the dam

To study the stability of the deposit slope in front of the dam on the left bank of A'Hai hydropower station, China, a total of eight typical sections B1-B8 are considered (seen from Fig. 1). The calculation model for section B6 is given in Fig.5. There are two potential sliding paths, noted by global and local sliding surface to be determined by setting different sliding surface entrances and exits. The rock and soil mechanical property parameters are listed in Table 1. The factors of safety along two different potential sliding paths are obtained under natural conditions before impoundment and operation period conditions after impoundment, which are given in Table 2. It can be seen that the factor of safety is between1.240 and 1.320 under natural conditions, which is more than the standard control value of 1.10 in construction condition of A'Hai Hydropower Station. The factor of safety calculated by modified rigorous Janbu method proposed in this paper is consistent with those obtained by other limit equilibrium methods, which indicates that it is feasible to use a cubic B-spline function to fit the inter-slice moments. Under normal water level conditions, the factor of safety is between

0.865 and 1.167, which is lower than the standard control value of 1.15 in the operation period of A'Hai Hydropower Station. Therefore, there is local instability of deposit slope in front of the dam, and some engineering measures should be taken.

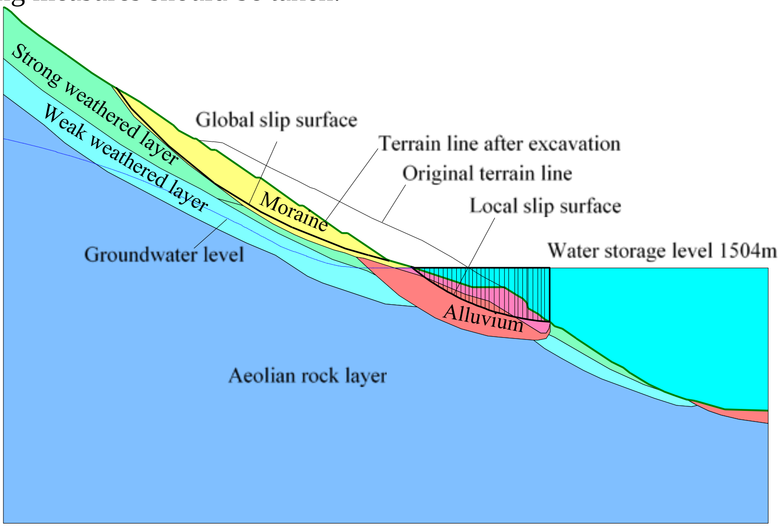

Figure 5. The model for B6 section deposit slope in front of the dam

Table 1. Parameters of rock and soil mechanical property for the deposit slope

Materials		Internal friction angle φ(°)	Cohesion C (MPa)	Natural bulk density (KN/m^3)	Wet bulk density (KN/m^3)
Deposit slope	Natural condition	30.5°	0.04	22.0	23.0
	Water-saturated softening	26.5°	0.02	22.0	23.0
Alluvium	Natural condition	26.5°	0.03	21.5	22.5
	Water-saturated softening	25°	0	21.5	22.5
Fine sand layer	Natural condition	25°	0.01	16.7	17.7
	Water - saturated softening	23°	0.005	17.7	-
Strongly weathered rock mass		31°	0.3	23.4	24.4
Weakly weathered rock mass		35°	0.5	24.7	25.7
Micro - weathered rock mass		47.7°	1	26.1	26.5

Table 2. The factors of safety for the typical section B6

Calculating conditions		The factor of safety					
		Swedish method	Simplified bishop method	Bishop method	Spencer method	M-P method	**Method of this paper**
Natural conditions		1.240	1.289	1.320	1.289	1.295	**1.286**
Operation period	Global sliding line	1.167	1.113	1.162	1.163	1.162	**1.144**
	local sliding line	1.074	0.865	0.937	0.991	0.991	**0.993**

3.3. discussion of deposit slope treatment measures

The decrease of safety factors is mainly caused by the rock and soil strength parameter reduction under operation period after impoundment. At the same time, the anchor bolt corrosion and landslide creep may occur, which makes it difficult to guarantee the long-term stability of the sliding body. Therefore, slope reduction should be an ideal choice to enhance the stability of the deposit slope in front of the dam of A'Hai Hydropower Station.

In slope stability analysis, geotechnical parameters usually have great effects on calculating the results of the factor of safety. For this reason, Parameter sensitivity analyses are also carried out. For section B6, the factor of safety is very touchy to the internal friction angle φ of alluvium under immersed state, and the cohesion C of moraine under natural states takes the second place. Based on comprehensive stability analyses of eight typical sections shown in Fig.1, the front edge of the deposit slope has an alluvial layer, which is under water level after impoundment. Thus rock and soil strength parameter reduction is a disadvantage to the deposit slope stability. So it is suggested that some specific treatment measures should be taken to avoid impacts on deposit instability caused by the alluvium layer being washed away before water storage.

4. Conclusions

The stability of deposit in front of the dam of A'hai Hydropower Station is studied using limit equilibrium method. Modification to the rigorous Janbu method is given to overcome its disadvantage of non-convergence. The cubic B-spline interpolation smoothing processes of inter-slice moment distribution of the rigorous Janbu method are demonstrated. It has shown that the stable convergence can be achieved using the calculating strategy proposed in this paper. The typical section B6 of deposit slope in front of the dam is taken as an example, and the factors of safety along two different potential sliding paths are obtained under natural loading conditions before impoundment and operation period loading conditions after impoundment. It is shown that the factor of safety is between1.240 and 1.320 under natural conditions. Under normal water level conditions, the factor of safety is between 0.865 and 1.167, which indicates that local instability of deposit exists.

Geotechnical parameter sensitivity analyses are also carried out. The factor of safety is sensitive to the internal friction angle of the alluvium under water saturated state. On the basis of comprehensive stability analyses of eight typical sections, slope reduction should be an ideal choice to improve the stability of deposit in front of the dam of A'Hai Hydropower Station, China. It is suggested that some specific treatment measures be taken to avoid impacts on deposit instability caused by the alluvium layer before water storage.

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