Stability analysis and risk assessment of a landslide in southwest of China

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Abstract—In this paper, a risk assessment method based on limit equilibrium method is proposed. It has been used to estimate the risk of forming wedge body in a landslide in southwest of China. According to the monitoring data and the result of stability analysis using limit equilibrium method and three-dimensional finite element method, we find that due to the rising of water table, the landslide tends to limit-equilibrium state. The displacement under normal condition is consistency with that of monitoring. It is possible to slide under dynamic condition, but the landslide cannot block the river totally. The research achievements have been used to make contingency planning and are of great significance.

1. INTRODUCTION

The landslide is located in the southwest of China. Two villages are about 5 km away from it, as shown in the figure 1. Due to the impoundment of a reservoir downstream, the water level was increased from 1876 m to 1906 m. About six months later, annular cracks appeared on the top of landslide and discontinuous lateral cracks grew up at the upstream and downstream of landslide. By now, cracks around the landslide have been joined, and maximum displacement of monitoring points have been reached to 3.2 m. Although the velocity of monitoring points have been decreased from 3.52 mm/h to 0.1 mm/d in half year, it’s still on the stage of creeping deformation, as shown in figure 2. In consideration of the huge volume of deformation areas (about 14 million cubic meters) and the narrow and shallow valleys, it may form barrier lakes, which have a great impact on the safety of the two villages and the reservoir downstream.
Figure 1. Location of the landslide.

The typical geological section of the slope has been shown in figure 3. The main strata, from surface to interior, are the debris layer, the rubble layer, the toppling layer and the normal rock respectively. Rock strata mainly dip toward mountain, and the attitude is N10º~20ºE, NW∠70º~80º. Under the action of long-term geological processes, rock strata presented flexural deformation forming a deep fracture zone. Above the deep fracture zone, a weak sliding zone was detected according to boreholes, which may be the main reason that result in this nonequilibrium evolution.
Figure 2. Curve of cumulative displacement.

Base on the monitoring data and the geological information, the landslide has a specific sliding surface, and the displacement from bottom to top is almost coordinated. So the key problem is to analyze the stability along the weak sliding zone and to estimate the risk of forming wedge body. At present, slope stability analysis methods mainly include limit equilibrium method [1-2], limit analysis methods based on the continuum model (finite element method, finite difference method, boundary element, and so on) [3-4] and numerical analysis method based on non-continuum model (such as DDA and DEM, rigid body-spring element, etc.) [5], among them the former two are widely used in project [6]. In this paper, limit equilibrium method and nonlinear finite element analysis were adopted to analyze the stability of the slope. And then, a risk assessment method is proposed to verify whether a barrier lake will form. The research achievements have been used to make emergency response plan and are of great significance.
2. ANTI-SLIDING STABILITY ANALYSIS

As showed in figure 3, the slope may slide along sliding zone or toppling fracture zone, these two cases are both analyzed. Slide 6.0 program was used for calculation, and Morgenstern-Price method was adopted. Sudden drawdown of water table condition stands for water table decreased to dead water level (1901m). Quasi-static method was adopted in dynamic analysis, and horizontal peak ground acceleration with exceeding probability of 10% in the future 50 years (0.15g) in this area was used. The mechanical parameters used are shown in table 1 and the results are showed in table II. We can see that the factor of safety decreased rapidly when water table rose. It’s a main reason of this nonequilibrium evolution. As to the factor of safety along sliding zone is lower, the slope is more likely to slide along it, especially under dynamic conditions.

| Rock mass       | Density kg/m³ | Friction | Cohesion (kPa) | Deformation modulus (MPa) | Poisson's ratio |
|-----------------|---------------|----------|----------------|--------------------------|----------------|
| Debris layer    | 2000          | 0.55     | 55             | 30                       | 0.35           |
| Rubble layer    | 2300          | 0.60     | 60             | 60                       | 0.30           |
| Toppling layer  | 2400          | 0.65     | 120            | 2000                     | 0.30           |
| Sliding zone    | 2000          | 0.55     | 40             | 30                       | 0.35           |
| Toppling fracture zone | 2300 | 0.60 | 120 | 2000 | 0.30 |

3. DEFORMATION STABILITY ANALYSIS

Three-dimensional finite element models are established based on the geologic investigation data to analyze deformation stability of the slope. The simulated range has been shown in figure 4. Tetrahedron elements are used. The bottom of the model is fixed and other boundaries are only fixed in the normal direction. The mechanical parameters used are also shown in Table 1. To get a factor of safety of the slope, strength reduction technique was adopted. The calculation conditions are the same as chapter 2. The results are showed in table III, we can see that it has a good consistency with the result obtained by
limit equilibrium method. The displacement under normal condition is also consistency with that of monitoring. The slope may be unsteady under dynamic conditions. The contour of displacement and maximum shear strain have been shown in figure 5 and figure 6. It should be specially explained that displacement under other conditions are computed based on normal condition, which have been reset to zero.

![Finite element model](image)

Figure 4. Finite element model (Elements: 481969, Nodes:93454)

| Load cases                        | Normal | Rainstorm | Sudden drawdown of water table | Dynamic |
|-----------------------------------|--------|-----------|--------------------------------|---------|
| Reservoir impounding              | 1.04   | 1.02      | 1.03                           | 0.99    |
(a) Normal condition

(b) Rainstorm condition

(c) Sudden drawdown of water condition
Figure 5. Contour of displacement (near section 3)
4. RISK ASSESSMENT OF RIVER-BLOCKING

Based on the above analysis, the slope would slide along sliding zone shown in figure 3 under dynamic condition. We assumed that cohesion of sliding zone decreased to zero when it slid. The landslide was divided into N slices, and every slice had the same width ΔL. As to an arbitrary slice i, we can get its force diagram shown in figure 7. We assumed that the slice slid along bottom sliding surface all the time. According to Newton's second Law, we can get the accelerated velocity of the slice in x direction (horizontal direction) was:

\[
a_i = \frac{\sum \left( \frac{W_i - U_i \cos \alpha_i}{W} \right) D_i - \sum \left( U_i\sin \alpha_i + \sum \left( \frac{U_i}{W} \sin \alpha_i \right) \right)}{1 + \sum \left( \frac{W_i}{W} \right)}
\]

Where, \( \sin \alpha_i, \cos \alpha_i \) are the dip angle of the bottom surface of slice i. \( g \) is gravitational acceleration. \( U_i \) is the uplift pressure of slice i. Moreover, as shown in the figure 8, \( N_i \) stands for the normal force of the bottom surface of slice i. \( H \) and \( Q \) are the normal force and the shear force between slices, whereas \( \Delta H_i \) and \( \Delta Q_i \) are the increment of the two variables. If we ignored the shear force between slices (\( \Delta Q_i \)), and the cohesion of sliding zone equaled to zero, equation (1) can be reduced to (2).

\[
a_i = \frac{\sum \left( \frac{W_i - U_i \cos \alpha_i}{W} \right) D_i}{1 + \sum \left( \frac{W_i}{W} \right)}
\]

So, we can get the accelerated velocity of every slices, and the initial velocity equaled to zero. In the next step, slice i moved to the position of slice i-1 and got a new state. During calculation all the slices were assumed to be connected, so they had the same horizontal accelerated velocity. The calculations have been realized by Python using a package named pyautocad. As shown in figure 8, we can get the
curve of velocity of landslide with time and its final shape. Although we ignored the internal energy dispersion between slices, the landslide still cannot block the river totally. The risk of instability was under control.

![Figure 8. Curve of velocity of the landslide with time and its final shape](image)

5. CONCLUSION
Due to the impoundment of a reservoir downstream, a landslide in the southwest of China was activated. Now it’s on the stage of creeping deformation. Based on the stability analysis using the limit equilibrium method and three-dimensional finite element method, the landslide was on the critical to unstable state. It is possible to slide under dynamic condition. To assess the risk of river-blocking, a method based on limit equilibrium method was proposed. The results showed that the landslide cannot block the river totally. The research achievements have been used to make emergency response plan and are of great significance.

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