Numerical Investigation on the Barrier Dam Risk Caused by Landslide-A Case Study on Caijiaba Landslide

ZENG Nianchang¹, LIU Bolong¹* and XIE Junning¹

¹School of Civil Engineering, Chongqing University, Chongqing, China 400045

*Corresponding author’s e-mail: liubolong3518@163.com

Abstract: To research the risk of barrier dam induced by landslide, Caijiaba landslide was studied as an example in the present study. The burst risk was assessed as well. To begin with, the region scope of quasi-landslide was obtained by stability calculation. Then the landslide process is analyzed by Partical Flow Code (PFC3D). On the basis of the numerical simulation results, the forming mechanism and motion characteristics of the barrier dam were analyzed. Subsequently, the Classical assessment model was employed to evaluate the burst risk of the barrier dam. Numerical results show that the highest body reaches 68.1 m. As a result, the riverway will be blocked by the debris, forming a weir dam. In addition, the body shape along upstream resembles a wedge. The fastest part of the sliding body is 8 m/s, and some of the debris flow stay on the hill still.

1. Introduction
Landslides are one of the most common and destructive geological disasters on earth [1-3]. When the landslide passes through the V-shaped isthmus, it will often lead to the blockage of the river at the foot of the slope and the formation of a weir dam, causing major safety hazards. For example, in 2018, two major landslides occurred in Jinsha River. The two landslides with dimensions as large as $2400 \times 10^4$ m³ and $850 \times 10^4$ m³ respectively, have created giant weir dams, posing a great threat to the safety of personnel and property [4]. Therefore, it is necessary to evaluate the risk of landslide of inducing weir dam.

Towards the formation mechanism and risk assessment of landslide, Zhou Li et.al. (2019) [5] adopted PFC3D discrete element software to conduct characteristic numerical simulation for the movement process of Baige landslide on jinsha River, and made the risk prediction for landslide. The simulation results fit highly with the field results. In this paper, PFC3D discrete element method is employed to simulate the landslide in the unstable region by combining the elevation data of Caijiaba Chongqing. According to the simulation results, the risk of landslide leading to the formation of dike dam in Longwangxi slope is analyzed.

The structure of this article is arranged as follows. Firstly, the geological overview of Caijiaba landslide is elaborated. Secondly, in order to affirm the unstable zone, the folding sliding method was adopted to calculate the regional stability. Moreover, the model was set in PFC3D and did the operation. Finally, the simulation result was analyzed to assess the risk of forming a weir dam.

2. Overview of Caijiaba Landslide

2.1. Landform
Caijiaba landslide is located in Yunyang County, Chongqing (Fig. 1). As shown in Fig. 2, the landslide is fan-shaped. The thickness of the soil layer is 4.40 m~10 m roughly, the thickness of the rock layer is about 13.8 m~30.7 m, and the debris volume of the landslide is about $1850\times10^4$ m$^3$ in total. In addition, Longwangxi, a tributary of the Yangtze River, lies in the toe of the landslide. The valley is in the shape of a deep “V”, and its width gradually increases from south to north (73 m-350 m), showing the horn shape at the confluence of the Yangtze River. The maximum water level is 5.5-7.4m during heavy rains.

3. Numerical Simulation on the Landslide

3.1. Determination of Landslide Area

In order to establish the landslide model, the quasi-landslide area was obtained through the regional stability calculation in this part. The thrust and stability of the landslide are calculated based on the folding sliding method, so as to determine the position of the potential sliding surface [6]. The calculation condition design is as follows: dead weight of rock and soil mass + surface load + rainstorms that occur every 50 years, and the safety factor is valued as 1.15.

Table.1 Stability criterion table

| Coefficient of stability | F$s<1.00$ | 1.00$<F$s<1.05$ | 1.05$<F$s<1.15 | F$s>1.15$ |
|--------------------------|----------|------------------|-----------------|---------|
| Stability                | Unstable | Metastable       | Basically stable| Stable  |

According to the calculated result, the stability of the landslide at different parts are as follows:

(1) Soil slippage zone: the calculated stability results are 1.048-1.108, which is in a metastable state;
(2) Shallow rock slip zone: Stability calculation results are 1.017-1.109, which is in a metastable state;

(3) Middle rock slip zone: the stability calculation results are 1.043-1.116, which is in a metastable state;

(4) Deep rock slip zone: The calculated stability is 1.115-1.202, which is in a basically stable state; Moreover, the soil slide zone, shallow rock slide zone and middle rock slide zone of Caijiaba landslide are under stable state under the design condition and have the risk of instability.

The stability calculation based on the drilling exploration, the representative drills was selected to full fill the stability calculation. According to the drills’ stability, the shape of the landslide was qualified. On account of the stability of the landslide at different parts, the landslide profile is determined, as shown in Figure 3.

![Figure 3 Sketch map of landslide section](image)

3.2 Establishment of landslide model

The landslide process was simulated by PFC3D. First of all, the macroscopic parameters which employed in this paper were calibrated by the uniaxial compression experiment [7]. The macroscopic mechanical parameters of soil mass used for calibration were the average physical properties of each exploration hole in the soil slippage zone obtained from geological survey, mainly including: slippage 20.85 kN/m³, cohesive force 20.72 kPa, Poisson's ratio 0.26, and elastic modulus 0.64× 10⁴ MPa. Reasonable model microparameters were finally determined, as shown in Table 2.

| Parameters | Definition | Value  |
|------------|------------|--------|
| Rₘᵣₜₜ   | Minimum radius of sphere /m | 5      |
| Rₘᵣₜₜ / Rₘᵣₜₜ | Radius ratio | 1.1    |
| ρ         | Density/kg·m⁻³  | 2085   |
| Eₙ        | Linear contact modulus /Pa | 0.44e10|
| K         | Stiffness ratio | 5      |
| μ         | Friction coefficient | 0.4    |
| Eₜ        | Binder modulus/Pa | 0.44e10|
| K'        | Bonding rigidity ratio | 5      |
| σₜ        | Normal bond strength /Pa | 2.6e6  |
| τₜ        | Tangential bond strength /Pa | 20.72e3|

According to the position of the potential sliding surface determined by the collapse-line sliding method, the slide surface profile of the quasi-landslide area was first registered in CAD for coordinate registration to form the datum plane after the landslide. Then it was imported into Rhinoceros software to establish the landslide bottom model, thus defining the sliding area and setting the sliding particles. The model included 36048 total particles.
4. Results and discussions

Combined with the mesoscopic parameters in Table 2, the parameters of the model sliding body were assigned and calculated. The distribution range and velocity of the slide body at different times are shown in Figure 4. The slide completely blocked the channel at about 30 s.

It can be seen from Figure 4 that most of the slides have slipped into the Longwangxi river channel after the whole body is stationary. However, due to the decrease of potential energy and the accumulation and blockage of the leading slides, the rest of the slides are still piled up on the hillside, forming unstable deposits.

![Figure 4 Sketch map of sliding process](image)

The energy transfer of the sliding body during sliding is shown in Figure 6. In the sliding process, the potential energy of the sliding body is equal to the sum of the collision energy, friction energy and kinetic energy between particles. It can be seen from the figure that the energy curves simultaneously...
reach a stationary state after 120 s, and the sum of potential energy is obviously equal to the sum of friction energy and collision energy, and the kinetic energy tends to zero. This is consistent with the conservation of energy.

According to statistics, the total volume of the landslide is about $1850 \times 10^4$ m$^3$. In the simulation, about two thirds of the landslide body, about $1200 \times 10^4$ m$^3$, slid into the channel. The accumulation body extended the upstream and downstream of the channel for more than 1,700 meters, presenting a shape of thick in the middle and thin at the end (Fig 5).

In this paper, the simulated sliding mass accumulation in the channel is presented in a typical section. Figure 5 (a) represents the position of the cutting surface of the sliding body accumulation, and Figure 5 (b) represents the broken line diagram of the accumulation body thickness along the river cutting surface, the average depth of river accumulation is 24.9 meters, and the deepest depth reaches 68.1 meters. The accumulation body appears as a wedge along the upstream of the river from the highest point of accumulation. Therefore, the slide will blocks the channel, forming the dam. According to the maximum accumulation thickness, the deepest point of the dam reaches 68.1 meters.

Figure 5  (a) Location of the section; (b) Accumulation thickness of the debris

Figure 6 Sketch map of energy transfer

To sum up, under extreme rainfall conditions in Caijiaba area, the stability within the area will be reduced, leading to landslides accordingly. According to the PFC3D simulation results, the Caijiaba landslide tends to be High-speed and short-range, with some slides piling up in longwangxi at the foot of the slope and the rest still piling up in the landslide area. Wedge-shaped DAMS with a maximum depth of about 68.1m will be formed in the river channel, and a weir dam will be formed after upstream convergence [8-9].
5. Conclusion
In this paper, PFC3D discrete element software is used to simulate the whole process of Caijiaba landslide, and it is concluded that the landslide will plug Longwangxi at the toe of the slope, forming a dam with a maximum height of 68.1 m. The main conclusions are as follows:

(1) Based on the local stability analysis under the condition of the extremely heavy rain, many areas of the landslide are in an under-stable state. Combined with stability analysis and elevation point cloud data, PFC3D discrete element software was used to simulate the landslide. In this simulation model, a ball-wall model is adopted, in which the wall is the slide bed boundary generated by the landslide terrain, and the ball is the rock and soil mass of Caijiaba landslide.

(2) The simulation results show that the sliding process of the landslide lasts about 120 s on the whole. The potential energy is mainly converted into the friction and collision energy between particles, and a small part of it is converted into the kinetic energy of particle flow. The landslide is a low-speed short-range landslide.

(3) The landslide is not completely piled up in the Longwangxi channel at the foot of the slope, and most of the rock and soil mass is not completely separated from the landslide area and piled up on the surface of the landslide area.

(4) The rock and soil mass piled in the channel, the maximum depth of 68.1 m, along the upstream of the channel, the accumulation body is wedge shape characteristics, providing good conditions for the formation of the barrier lake. The simulation results can provide some reference for process protection and management.

Reference:
[1] Wen C., Peng H., Jin K. (2017) Study on the Water Surge Height Line of Landslide Surge of Linear River course Reservoir Based on FLOW-3D Journal of Environmental Science and Engineering, (5): 293-298.
[2] Luo G Z, Gao W W, Wang G W, et al. (2020) Risk analysis of surge disaster and slope instability on reservoir bank. The Chinese Journal of Geological Hazard and Control, 31(1): 8-17.
[3] Zhao T, Dai F, Xu N W. (2016) Coupled DEM-CFD investigation on the formation of landslide dams in narrow rivers. Landslides, 14(1): 189-201.
[4] Xu Q, Li W L, Dong X J, et al. (2017) The Xinmocun landslide on June 24, 2017 in Maoxian, Sichuan: characteristics and failure mechanism. Chinese Journal of Rock Mechanics and Engineering, 36(11): 2612-2628.
[5] Zhou L, Fan X M, Xu Q, et al. (2019) Numerical simulation and hazard prediction on movement process characteristics of Baige landslide in Jinsha river. Journal of Engineering Geology, 27(6): 1395-1404.
[6] Cundall P A, Strack O D L. (1979) A discrete numerical model for granular assemblies. Geotechnique, 29(1): 47-65.
[7] Headquarters of Geological Disaster Prevention and Control in the Three Gorges Reservoir Area. (2014) Technical requirements of geological prospecting for the three gorges reservoir area. China University of Geosciences Press, 2014.
[8] Wang S H, Hu R L, Tong L Q. (2015) Inventory of landslide dams at Himalaya, China and analysis of their spatial characteristic. Journal of Engineering Geology, 2015(3): 361-372.
[9] Dong X. (2016) Research on the disaster chain modes of avalanche and landslide and the river blocking dam risk assessment. Sichuan: Chengdu University of Technology.