Numerical investigation of a post-earthquake rockslide in Wenchuan using discrete element method

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Abstract. The development of fractures in the mountain ridge in meizoseismal area may lead to fatal rockslides. In this paper, we take a post-earthquake rockslide in shattered mountain located on the left bank of Yinxingping (YP) debris flow gully in Wenchuan as an example. Firstly, we use field investigation, UAV aerial photography and remote sensing to find out its basic characteristics and initiation mechanism, and divide the landslide area into source area, transitional area and depositional area. Then, the dynamic characteristics are evaluated by discrete element method. The simulation results show that the sliding mass disintegrates rapidly into many small blocks after initiation. Due to the steep terrain, the maximum velocity and displacement of the sliding blocks in the movement process reach 23.89 m/s and 130.64 m, which belongs to high-speed short-length rockslide. In addition, there are four groups of large-scale fractures developed at the rear edge of YXP rockslide, and it is found that they may continue to expand under the condition of rainfall through field investigation, so the slope is still in an unstable state. This study can provide a reference for the hazard assessment and prevention of post-earthquake rockslide.

1. Introduction

The Longmenshan fault zone is located in the transition zone from Qinghai-Tibet Plateau to Chengdu Plain, which is also one of the regions with high incidence of geological disasters in the world. Especially after the 2008 Wenchuan earthquake, the number and scale of geological disasters in this area have a pulse increase (Huang et al. 2012). Under the action of earthquake, a large number of cracks are produced in the rock mass of mountain ridges. These cracks are usually hidden by vegetation, but the disaster may be devastating (Yan et al. 2020). The development of cracks can be divided into two types. One is retrogressive development. This development type may cause some small-scale rockslides. These rockslides have obvious omens and can be prevented in advance. Another one is the integral sliding, which often leads to large-scale rockslides. It is difficult to prevent and often causes huge losses because of its sudden nature (Fan et al. 2019). For example, the rockslide in Sanxi village in 2013 (Yin et al. 2016) caused 166 deaths. In 2017, the Maxian rockslide caused 83 deaths (Fan et al. 2017).

In present, numerical simulation has become an important tool for the study of post-earthquake rockslide because of its complex dynamic characteristics. Some scholars have applied the finite
difference method for rockslide simulation (Yin et al. 2015; Longoni et al. 2014). Wei et al. 2019 used PFC$^{3D}$ to study the affected range of unstable slope in the Mabian, and acquired consistent results. But it is difficult to reveal the failure mechanism of rock mass. Huang et al. 2019 used two-dimensional discrete element DDA$^{2D}$ to simulate the Xinmo rockslide, which can easily reveal its dynamic characteristics. Therefore, the discrete element method may be the most realistic simulation method, which can simulate not only the fracture failure characteristics of rock mass, but also the dynamic characteristics of rock mass (Espada et al. 2018). 3DEC, as a representative of discrete element method, has been widely used in the study of dynamic characteristics of rock rockslide. The code has a friendly graphical interface and better compatibility, which is helpful for the establishment of model. In addition, it can simulate the rock mass cut by fractures for a better application in meizoseismal area. For example, Liu et al. 2021 implanted the discrete fracture network into 3DEC to study the influence of fracture density and friction angle on the movement characteristics. Wu et al. 2018 studied the erosion effect of Hsien-Du-Shan rockslide on the material along the movement path in Taiwan. These studies demonstrate the wide applicability and effectiveness of 3DEC.

Based on the above research, we utilize the 3DEC to study the dynamic characteristics of post-earthquake rockslide. Taking Yinxingping (YXP) rockslide in Wenchuan as an example, abundant field investigation data helps us to find out the basic characteristics and causes of the rockslide. Based on aerial photography and remote sensing, a numerical model of YXP rockslide was established and applied in the simulation. Due to the high degree of weathering and fragmentation of rock mass in source area, a uniformly distributed discrete fracture network was used to establish the cracks in the rock mass. The simulation results reveal the movement mode and dynamic characteristics of the post-earthquake rockslide from the aspects of the velocity and displacement. After that, we analysed the possibility of further development of the rockslide through the field investigation of the residual cracks in the ridge area. This research can help us to deepen the understanding of the movement mode and disaster mechanism of post-earthquake rockslide in meizoseismal areas.

2. Geological setting

2.1. Geological setting

YXP rockslide is located in Yinxing village, Wenchuan, Sichuan Province, China, with a geographic coordinate of 103° 29′ 34.6″ E, 31° 10′ 43.3″ N. It is occurred on the left bank of YXP debris flow gully, about 800m away from the gully mouth. The G213 national highway and Dujiangyan-Wenchuan expressway are located in the front edge of the gully mouth. YXP rockslide is located in the front of Longmenshan nappe belt in the northwest of Sichuan Basin (Fig. 1). The landform of study area is low to middle mountain with steep terrain. Affected by the southeast warm and humid air flow, the study area has abundant rainfall and heavy rain in summer. The average annual precipitation is 1253.1 mm and the maximum daily precipitation is 269.8 mm.
The YXP rockslide area can be divided into source area, transitional area and depositional area (Fig. 1, 2). The slope of source area is steep, about 60°. The area of sliding region is about $3.14 \times 10^4 m^2$, and the average thickness is about 5.8m, so the total volume is about $18.22 \times 10^4 m^3$. In the Wenchuan earthquake, a large number of cracks caused in the source area. Under the rainfall situation, the rainwater infiltrates along the cracks, which leads to the saturation of sliding mass and the increase of pore water pressure. When it reaches a critical value, the rockslide will initiate. The transitional area of YXP rockslide is short, the length of this section is about 120m, and the slope angle is 47° (Fig. 2, 3b). Therefore, there will be an obvious acceleration process in this area, but the process is short. Due to the terrain condition of high in the middle of transitional area and low on both sides, the sliding mass slides down approximately in two directions. When the sliding mass reach the depositional area, they begin to converge. Because the bottom of the depositional area is the main gully of YXP debris flow, the deposit is not a regular fan, but inclines to the downstream of YXP gully (Fig. 3c).

According to the in-site investigation, the sliding plane at the rear edge of YXP rockslide is very obvious and smooth (Fig. 3a). The deposit almost blocks the channel at the foot of the slope (Fig. 3b). The rockslide material is mainly quartzite gravel, and the relative particle size is larger, so it has less influence on the small-discharge stream in YXP gully. However, if a large debris flow occurs, the
discharge may be enlarged and the downstream will be more seriously damaged due to the blocking effect.

![Figure 3. Photos of scarp, transitional area (a) and depositional area (b) of YXP rockslide.](image)

3. Method and model setting

3.1. The discrete element method

The discrete element method 3DEC has been used in the world widely which uses an explicit solution (Cundall and Damjanac 2009). By discretizing each block into tetrahedral elements, the mechanical contact analysis of the block can be realized (Einstein et al. 1983). In 3DEC, contact can be modelled mathematically. In the normal direction, the joint normal stiffness, $K_n$, is parallel to the normal contact damper. In the tangential direction, the joint tangential stiffness, $K_t$, and the tangential contact damping are in parallel, and connected with Mohr Coulomb slider, $S_{m-c}$. The code divides two-dimensional contact points with polygons into edge to edge, vertex to vertex and vertex to edge geometrically. One edge to edge contact can be converted into two vertices to edge contact (Fig.4).

![Figure 4. The calculation circle in discrete element method.](image)

3.2. Model setting

We established a two-dimensional model of the rockslide based on the UAV aerial photography and the ALOS digital elevation model. The sliding mass and rock bed are divided by the interface. It is needed to keep the rock bed fixed, and fix the surrounding and bottom boundary at the same time in simulation. The fractures sliding mass are established by cutting the sliding mass with fracture network uniformly distributed along X, Y and Z directions. The number of joints and blocks after cutting are 2637 and 9261 respectively. Before the simulation, the gravity field should be applied to the model by setting the sliding mass and rock bed as the elastic model and giving gravity.

We set the parameters of sliding mass, rock bed and joints before the simulation by referring to the Xiaogangjian rockslide, which is also located in the meizoseismal area, about 69km away from YXP rockslide. The rockslide was also cracked in the Wenchuan earthquake, but it was not triggered by rainstorm until January 19, 2016, which is similar to YXP rockslide in geological conditions and
Inducing factors (Liu et al. 2021). The specific values are shown in Table 1. It should be noted that the parameters of sliding mass and joint are saturation values, because they are triggered by rainfall. When simulation timestep reaches 16000 steps, the corresponding actual physical time reaches 45.67s according to the relationship of simulation timestep and actual physical time come with the code.

| Parameters          | Value       |
|---------------------|-------------|
| Fixed rock bed      |             |
| Young’s modulus (GPa) | 3.50       |
| Poisson’s ratio     | 0.35        |
| Density (kg/m³)     | 2450        |
| Sliding mass        |             |
| Young’s modulus (GPa) | 1.20       |
| Poisson’s ratio     | 0.25        |
| Density (kg/m³)     | 2550        |
| Joint               |             |
| Cohesion (kPa)      | 0.00        |
| Friction angle (°)  | 13.0        |
| Normal stiffness, \(K_n\) (MPa/m) | 3.00 |
| Shear stiffness, \(K_s\) (MPa/m) | 3.00 |
| Local damping ratio, \(\alpha_d\) | 0.03 |
| Model               |             |
| Number of joints    | 2637        |
| Number of sliding mass blocks | 9261 |

4. Result

4.1. Characteristic of displacement

Displacement is one of the main characteristics of rockslide, which can not only help us to understand the positions of sliding mass at different times, but also show accumulation characteristics of sliding mass in the movement process (Wang et al. 2020). When \(t = 6\) s, the sliding mass has initiated completely. Because the rock mass on the front has no excessive constraints, its displacement is larger, and the maximum displacement is 37.71 m (Fig.5a). When \(t\) reaches 12 s, the maximum displacement is 94.18m (Fig.5b). At this time, the upper rock mass migrated to the transitional area and depositional area, and experienced long-distance acceleration and mutual collisions, and the volume of rock mass increased significantly. When \(t = 18\) s, the maximum displacement is 128.41 m. Except that a few of rocks stay in the source area, most of the rock mass have completed the deposition process (Fig.5c).

From the displacement distribution of the accumulation area, it can be seen that the displacement of the lower depositional mass is smaller than that of the upper depositional mass, which indicates that the material in the front edge of the sliding mass reaches the bottom of gully earlier and starts depositing, and the materials in the rear edge deposit upward in turn. When \(t = 45\) s, the movement process of the sliding mass is basically stopped, but the gully was blocked (Fig.5d). If the debris flow in Yinxing gully occurs, the rockslide materials are important supplement source, which could enlarge the discharge of debris flow and cause serious damage.
4.2. Characteristic of velocity

Another important characteristic of rockslide is velocity. Velocity reflects the energy change of the sliding mass in the movement process, and also affects the impact force of rocks (Wang et al. 2020). When $t = 6$ s, the sliding mass just initiates, and the maximum velocity of individual blocks in surface reaches 15.50 m/s, but the average velocity is about 10 m/s (Fig.6a). When $t = 12$ s, the maximum velocity of blocks is 23.89 m/s, and the overall average velocity is close to 15.00 m/s (Fig.6b). As the sliding mass continues to move, the sliding mass begins to deposit when the $t$ reaches 18 s (Fig.6c). At this time, the maximum velocity is only 14.88 m/s, which also only exists in individual blocks. At this time, the velocity of the material that firstly reaches the bottom of the gully decreases rapidly to 0 m/s, but the rocks arrived later still has a velocity of 3~8 m/s. When $t = 45$ s, the velocity of almost all the rock mass decrease to zero except sporadic rocks at rear edge, which means that the movement process is close to stop (Fig.6d).
5. Discussion

Many rock masses in meizoseimal area produce numerous cracks under the action of earthquake, and the development of these cracks controls the occurrence of rockslide (Tinti et al. 2005). According to the field investigation, we found 4 groups of tension cracks (C1-C4) at the rear edge of YXP rockslide. The sizes of these cracks are shown in Fig. 7. It is necessary to set some displacement monitoring points in these places. Research shows that post-earthquake geological disasters may last for 10-25 years or more, and the main reason may be related to the uncertainty of the breakthrough of these cracks (He et al. 2011). Of course, it is impractical and impossible to find all the seismic cracks only by manpower. From the current technology point of view, 3D laser scanning of the designated area may be a research direction of the identification of this kind cracks in the future study (Glenn et al. 2006).
6. Conclusion

Based on field investigation and numerical simulation, the dynamic process of YXP rockslide is analysed, and the development of cracks in the rear edge of the post-earthquake rockslide is discussed. The conclusions are as follows:

1. The YXP rockslide initiated and disintegrated under the condition of rainfall, and then the sliding mass run downward along a direction and deposited at the lower area of the rockslide. The acceleration of the sliding mass under the action of gravity is due to the large slope angle in the source area and transitional area.

2. The movement process last for about 45s. During the process, the maximum velocity of the local block is 23.89 m/s, and the maximum displacement is 130.64 m. Therefore, the YXP rockslide is a high-speed short-distance rockslide.

3. At present, there are still many fresh cracks in the rear edge of the YXP rockslide, which may develop and lead to the recurrence of the rockslide under the condition of rainfall, so the rockslide is still in an unstable state.

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Declaration of competing interest
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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