Numerical Modeling and Analysis of Open-pit Mine Landslide Based on Oblique Photogrammetry and GDEM-GAVA

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Abstract. Open-pit mine landslides are dynamic disasters characterized by high nonlinearity and uncertainty. This paper presents a simulation of slope instability in an open-pit mine located in Guangdong Province, China, using the GDEM-GAVA method. Through an analysis of the source area, landslide mass, and the entire study area model, this research provides insights into the main development process of landslide disasters in open-pit mining areas, the characteristics of landslide mass movement paths, and the accumulation features in the severely affected areas. The findings reveal that the overall planar shape of the landslide mass in the open-pit mining area is elliptical, with the development process of the entire landslide accumulation area displaying two distinct zones: the upper step accumulation zone and the middle-lower step accumulation zone. The depth of the sliding body ranges from approximately 1 to 10 meters. The affected area spans about 420 meters in length, 100 meters in width, and 190 meters in height, with a maximum accumulation thickness of approximately 10 meters. The impacted area covers an approximate area of 40,000 square meters. These results can serve as a reference for subsequent safety production measures related to open-pit mine landslides caused by natural disasters.

Keywords: open-pit mine; numerical simulation; oblique photography; point cloud model; landslide.

1 Introduction

Open-pit mine landslides are regarded as one of the most severe geological hazards in the field of mining. In recent years, there has been a growing focus on employing numerical simulation methods to investigate open-pit mine landslides, gradually becoming a focal point of academic attention.

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Numerical simulation methods are highly accurate and reliable, providing more detailed analysis and results. Currently, numerous researchers have utilized numerical simulation methods to investigate the mechanisms and patterns of landslides. Among them, the Material Point Method (MPM) is capable of effectively analyzing large deformations and post-failure displacement of landslides [1-3]. FLAC3D for parameter inversion has garnered significant attention from scholars [4-6]. Additionally, the Continuum Discontinuum Element Method (CDEM) has also been an effective approach in landslide research [7]. These studies are not only of significant importance for a profound understanding of the mechanisms and characteristics of open-pit mine landslides but also provide crucial scientific foundations for their prevention and control.

Traditional three-dimensional numerical modeling methods for open-pit mines typically involve three steps: geological exploration, geometric modeling, and mesh generation. The geological survey phase is often conducted through manual surveying, which introduces uncertainties in measurement accuracy and consequently leads to low modeling precision. The limitations of traditional modeling methods include low accuracy, high costs, and long cycles [8]. These issues significantly hinder the achievement of large-scale and high-precision numerical calculations for open-pit mines. With the development of unmanned aerial vehicle (UAV) technology, the use of oblique photogrammetry methods has emerged as a means to rapidly construct high-precision three-dimensional realistic models of open-pit mines, thereby compensating for the limitations of traditional methods [9-10].

Open-pit slope instability is a highly complex geomechanical problem, involving various factors such as rock mechanics, hydrogeology, and meteorological conditions. Therefore, the utilization of accurate numerical computational models and appropriate numerical methods can aid in better understanding and predicting the mechanical behavior of slope instability. In this study, to accurately assess the evolutionary process and scale of open-pit slope instability, the GDEM-GAVA software and oblique photogrammetry technology were employed for precise modeling and prediction of the scale of slope instability in open-pit mines. GDEM-GAVA is an efficient numerical simulation software for explicit particle dynamics, based on hybrid parallelization with multiple cores of CPU/GPU. The software employs a finite volume method with vertical integration and utilizes a Riemann solver, significantly reducing computational complexity. Its notable capability lies in efficiently simulating the disaster process of geological events, even extending to areas covering millions of square meters.

2 The basic characteristics of a specific open-pit mining disaster point

A certain open-pit mine in Guangdong Province covers an area of 338300 square meters. The mining area is characterized by hilly topography, with a general slope from north to south. The ground elevations range from 259 to 72 meters above sea level, with a local erosion datum at an elevation of 30 meters. The height of the open-pit slopes exceeds 200 meters, with a covering layer slope angle ranging from 40 to

45 degrees, step heights between 10 and 15 meters, and slope face angles of 71 to 75 degrees. The working platform width ranges from 42 to 58 meters.

The slopes in this quarry are characterized as high and steep, with the presence of unfavorable geological bodies and fractured zones in the northwest. These factors contribute to poor stability. Consequently, the fracture zones in the mining area are prone to natural geological hazards such as landslides, which pose risks to production safety in the mining area. Figure 1 illustrates the overall layout of the open-pit mine.

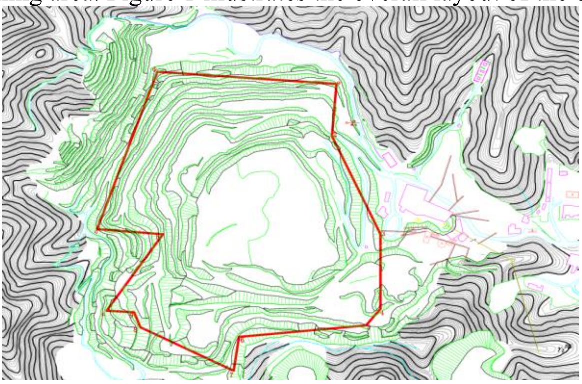

Fig. 1. Distribution of open-pit mine

3 Finite Volume Method Based on Depth Integration

The Savage-Hutter model is a set of quasi-three-dimensional hyperbolic partial differential equations that are used to describe the frictional flow of a landslide[8~9]. The equations are as follows: (1)~(3) The equations take into account the depth of the landslide, the depth average velocity in the x and y directions, and the friction angle of the bed surface. This model is able to capture two important characteristics of landslide mass movement process, friction characteristics and thin layer characteristics, and is able to limit the amount of calculation within a reasonable range. Therefore, it is very suitable for describing landslides, especially giant landslides, movement disaster process, and can also reflect the impact of terrain. The finite volume method of depth integration is mainly used in GDEM-GAVA.

$$\frac{\partial h}{\partial t}+\frac{\partial hu}{\partial x}+\frac{\partial h\mathrm{v}}{\partial y}=0 \tag{1}$$

$$\frac{\partial hu}{\partial t}+\frac{\partial}{\partial x}[\mathrm{hu}^2+\frac{1}{2}\mathrm{g}_z\mathrm{h}^2]+\frac{\partial\,\mathrm{huv}}{\partial y}=h[\mathrm{g}_x-\frac{u}{\|V\|}\mathrm{g}_z\tan\delta-g_z\frac{\partial b}{\partial x}] \tag{2}$$

$$\frac{\partial hv}{\partial t}+\frac{\partial huv}{\partial x}+\frac{\partial}{\partial y}[\mathrm{hv}^2+\frac{1}{2}\mathrm{g}_z\mathrm{h}^2]=h[\mathrm{g}_y-\frac{v}{\|V\|}\mathrm{g}_z\tan\delta-g_z\frac{\partial b}{\partial y}] \tag{3}$$

Where, $U = (h \quad hu \quad hv \quad hc)^T$, $F = (hu \quad hu^2 + \frac{1}{2}gh^2 \quad huv \quad huc)^T$, $G = (hv \quad huv \quad hv^2 + \frac{1}{2}gh^2 \quad hvc)^T$ .h is the water depth, u and v are the flow velocities in two directions of the plane, and c is the sediment concentration.

4 Constructing a computational model of an open-pit mine based on oblique photography

The construction of a numerical computational model for open-pit mines involves three main steps. Firstly, the specific location of the landslide area is determined based on profile CAD drawings and unmanned aerial vehicle (UAV) data. Secondly, a geological model of the potential sliding mass is created based on the identified landslide location, and the geometric information of the sliding mass is incorporated into the main computational model. Lastly, the generated geometric model is divided into a computationally feasible mesh model according to the software requirements. Through these steps, an accurate numerical model can be constructed to simulate the potential hazards and disaster scale of landslide events in open-pit mines.

The specific modeling process for the numerical calculation model of an open-pit mine is illustrated in Figure 2.

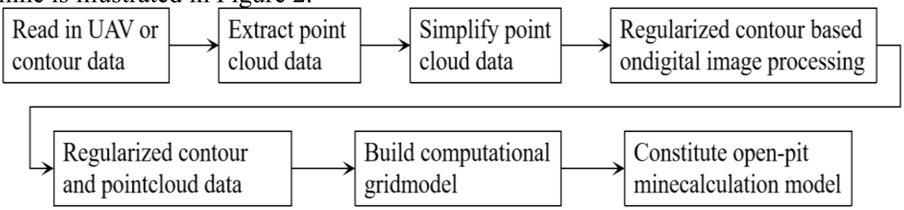

Fig. 2. Open-pit Mine Modeling Process

After the extraction of the geometric model data, based on the point-to-point elevation modeling in the GDEM-GAVA software, the modeling of the bottom bed of the tailings reservoir and the surrounding area was constructed. According to the site survey, it is determined that the volume of accumulation above the most dangerous sliding surface is $80 \times 10^4 m^3$. The global interpolation calculation model of the tailings pond is shown in Figure 3.

Fig. 3. the distribution of potential fractured zones in the mountainous area of the mining site

Further extraction of point cloud data was performed based on UAV data, and a regularization method using digital image processing was employed with the assistance of third-party software for point cloud data filtering and simplification. The pass-through filtering technique was utilized to extract contour point clouds from the point cloud model. This method involves clipping the point cloud model based on specified dimensions and intervals, retaining only the points within the specified range. In this case, the filtering dimension was set in the direction of the open-pit mine depth, and the filtering range was set to a smaller interval. The resulting filtered points obtained through pass-through filtering are shown in Figure 4.

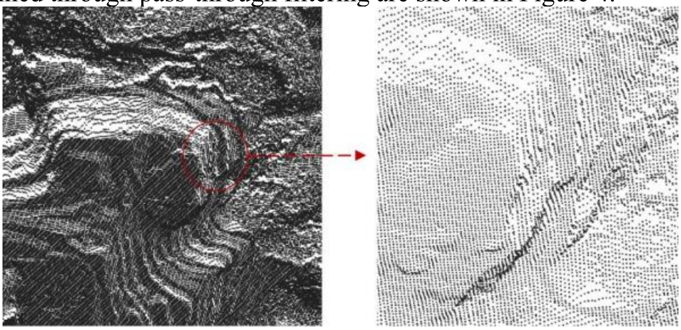

Fig. 4. illustrates the process of point cloud extraction from UAV data.

After completing the extraction of geometric model data, a point-to-point elevation modeling was performed using the GDEM-GAVA software to construct the models of the open-pit mine and its surrounding area. Due to slope excavation, the rock mass originally located within the ground surface is exposed, disrupting the initial stress equilibrium within the slope rock mass. The slope surface is subjected to the movement of the exposed rock mass under the influence of its self-weight and secondary stress field. The local residual soil and the poor hydraulic properties of the highly weathered layer on the ground surface make it susceptible to erosion and instability during the rainy season due to water infiltration. Based on the physical and mechanical properties of the rocks, the geological materials in the mining area are classified into residual slope deposit loose-weak soil engineering geological rock group and moderately weathered to highly weathered semi-hard-hard rock engineering geological rock group. The thick overlying layer is prone to softening and disintegration when exposed to water, leading to poor slope stability. Under increased mining intensity, it may cause slope instability and trigger geological hazards such as collapse. Based on field surveys, the volume of the most critical landslide mass above the most dangerous sliding surface was determined to be 50,000 cubic meters. The overall interpolation calculation model of the open-pit mine is shown in Figure 5. Point cloud data and contour modeling data were used for detailed modeling and meshing, with a total of 500,000 elements divided.

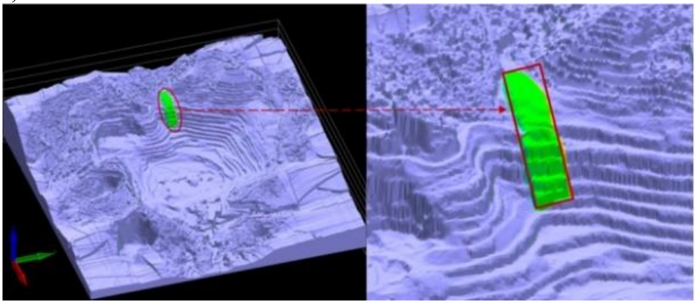

Fig. 5. illustrates the process of point cloud extraction from UAV data.

When using the finite volume method based on depth-integrated approach for modeling and simulation in the debris flow module, it is known from the hyperbolic partial differential equations in the calculation process that the key control parameter is the contact friction between the landslide mass and the sliding bed. Therefore, the focus of the simulation parameters is the strength characteristics under the saturated state of the open-pit mine material, mainly represented by the internal friction angle. Based on available data, the average internal friction angle in the open-pit mine material source area is approximately 25°. To accelerate convergence and enhance the stability of the simulation results, a Courant number of 0.2 is set.

5 Analysis of Calculation Result of Open-pit Mine

The overall process characteristics of the open-pit mine slope landslide are shown in Figure 6. The geological cover of the upper part of the ore body consists of residual slope deposits, granite strong-medium weathering layer, and quartz sandstone strong-medium weathering layer. The residual slope deposits have an average thickness of about 12m, the strong weathering layer has an average thickness of about 7m, and the medium weathering layer has an average thickness of about 3m. The presence of the strong weathering layer results in poor hydraulic properties, making it prone to disintegration when encountering water. Therefore, there is a possibility of landslides in the surrounding mountains of the mining area. The potential geological landslide area is estimated to be approximately 50m × 50m, with a discrete depth of 10m. After the calculations are completed, the results are statistically analyzed, and the volume of the geological landslide mass is estimated to be approximately 30,000 cubic meters.

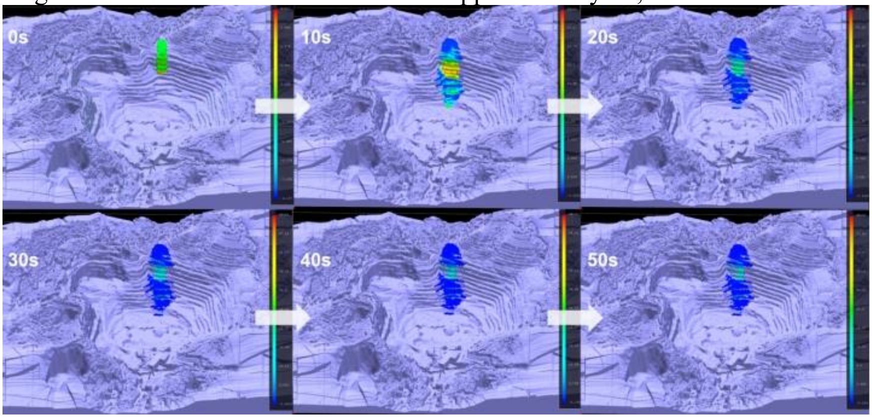

Fig. 6. Velocity cloud map of open pit slope failures at different time intervals

The mining operation has created irregular steps with 12 levels, where the step height ranges from 15 to 20 meters and the slope angle varies from 50 to 80 degrees. Based on geological data, the fragmented steps in the western part of the mining area are identified as potential landslide zones, with an approximate area of 120m x 50m and a discretized depth of 10 meters. Upon completion of the calculations, the statistical analysis of the results reveals that the landslide volume of the open pit steps is approximately 20,000 cubic meters, and the sliding distance at the front edge of the sliding mass is around 480 meters.

Model Calculation Time 0-10 seconds: During this period, the main sliding mass moves extensively towards the upper step area. Simultaneously, the step landslide material cascades into the lower steps and accumulates in the water-logged area at the bottom of the mining site. This stage is characterized by the strong impact and deposition of the upper sliding mass onto the middle and lower mining areas, as well as the low-lying valleys. It involves high-speed movement and large-scale transport of debris flows.

Model Calculation Time 10-50 seconds: In this stage, the kinetic energy of the main sliding mass is largely dissipated, and the movement primarily involves the transportation of the accumulated sliding mass in the middle section.

The development process of the entire sliding and accumulation area in the open pit mine landslide exhibits two distinct zones, as shown in Figure 7. These zones are the upper step accumulation area and the middle-lower step accumulation area. This differentiation arises from the steep angle and the solid nature of the central step, which prevents fragmentation and inhibits significant accumulation.

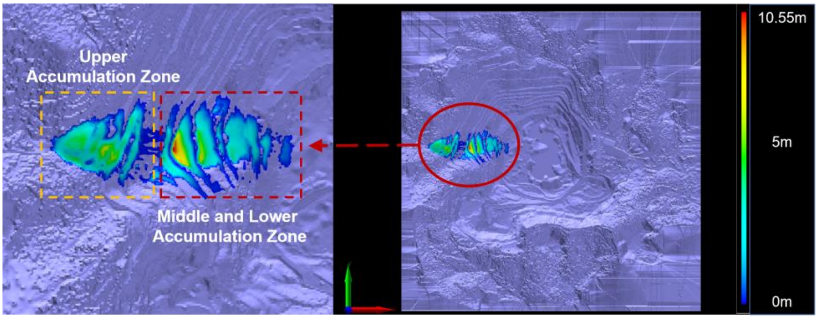

Fig. 7. illustrates the extent of the landslide accumulation at 50 seconds in the open pit mine.

The extent of the disaster in the open pit mine at the end of the calculation is shown in Figure 8. Under the influence of gravity, the sliding mass moves downward towards the lower part of the mining area, with a burial depth ranging from approximately 1 to 10 meters. As the kinetic energy dissipates, the lower part of the sliding mass accumulates in the stepped areas and low-lying valleys, forming distinct zones. The overall shape of the landslide is elliptical, with a length of approximately 420 meters, a width of approximately 100 meters, and a height of 190 meters. The maximum accumulation thickness is about 10 meters, and the affected area is estimated to be over 40,000 square meters.

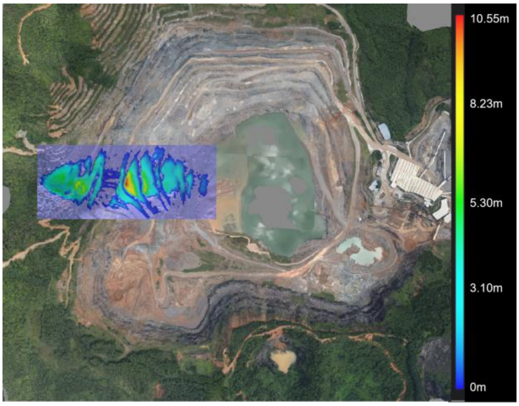

Fig. 8. illustrates the primary extent of the sliding mass and the accumulated depth at the final moment of the open pit mine landslide

6 Conclusion

In conclusion, a numerical modeling and simulation study was conducted on the geological hazards caused by mass and step landslides in an open-pit mine in Guangdong Province. The identified developmental stages highlight the extensive sliding of the mass to the upper step area within the initial 0-10 seconds, followed by kinetic energy dissipation in the subsequent 10-50 seconds. Zoning characteristics manifest in an elliptical shape with distinct upper step and middle-lower step accumulation zones, attributed to the stable rock mass of the middle step. The affected area, with a volume of approximately 30,000 cubic meters, demonstrates dimensions and characteristics such as a length of about 420 meters, width of about 100 meters, and a height of approximately 190 meters. This comprehensive analysis enhances our understanding of landslide instability processes, offering valuable insights into potential risk areas and serving as a foundational reference for safety management strategies in preventing open-pit mine landslides triggered by natural hazards.

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