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Numerical Simulation of Inverted Pear-shaped Landslide Based on Discrete Element Method

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Abstract

Landslides are very common geological hazards. Due to the different forms, scales and types of landslides, their formation mechanisms are different, which in turn cause the degree of damage and treatment measures are also quite different. As a rare type of landslide, "inverted pear-shaped" landslide has special planar characteristics and formation mechanism. This paper analyzes and summarizes the different causes and formation processes of this type of landslide. MatDAM, a discrete element numerical simulation software, is used to numerically simulate the movement process of this type of landslide. According to the model comparison before and after each slide, the pushing and wrapping effect of the subsequent slide on the residual slide of the previous slide is obtained. From the perspective of numerical simulation, quantitative data support is provided for the qualitative formation mechanism study.

Keywords

Inverted Pear-shaped Landslide; Multiple Slides; MatDEM; Numerical Simulation.

1. Introduction

China's vast territory, complex and changeable geological tectonic movement, and special topography and geomorphology formations have made our country susceptible to the attack of geologic disasters. As a common form of geological disaster, landslides bring great losses and threats to people's lives and production due to their suddenness, large scale, and unpredictability. Research on landslide disasters is an important topic in the field of geoengineering and an urgent need to safeguard people's lives and properties.

In the field of landslide research, inverted pear-shaped landslide[1] as a special form of landslide, its formation mechanism and stability characteristics have not been fully studied and explored compared with other types of landslides. The formation mechanism of inverted pear-shaped landslides involves complex geological factors, including topography, stratigraphic lithology, hydrological conditions seismic activities, and other factors. The stability evaluation of inverted pear-shaped landslides can not only provide a scientific basis for the prevention and control of landslide disasters but also help to guide the prevention and control of geological disasters in engineering practice. Since the 1950s, experts and scholars at home and abroad have begun a series of studies on the mechanism of landslide formation and achieved fruitful research results[2-6], the domestic research on the mechanism of landslide formation started late, but based on previous research, by combining with the geological background conditions, a large number of studies have been carried out from various aspects such as physics, mechanics and other aspects of the mechanism of landslides, and fruitful results have been achieved[7-11]. Although countless researchers at home and abroad have achieved certain research results on the mechanism of landslide formation, due to the uncertainty of landslide factors, which are the key to the study of landslides, it leads to the fact that there is no relatively perfect and mature system for the mechanism of landslide formation in the country at present, and different landslides correspond to different research results of mechanism, and it is very difficult to apply the mechanism of landslide formation with the same characteristics It is difficult to apply the landslide formation mechanism with the same characteristics to similar landslide work[12-16].

With the development of information technology, the use of numerical simulation analysis methods is also increasing, researchers have begun to cross the traditional geo-engineering theory and computer disciplines, and the use of computer-integrated computational methods for the relevant geological numerical simulation analysis, from the point of view of the approximate equivalence of simulation, expanding the limitations of the original calculation of geotechnical engineering. Liu Hongshuai[17] and other numerical simulations by comparing several methods of finite element method is a multi-field coupling down the study of reflecting the stress changes in the geotechnical body and small deformation problems, which is now more mature, with a variety of structural models, can be refined, accurate simulation and calculation of geotechnical engineering problems. Fast Lagrangian method[18], using the same basic assumptions as the finite element method, based on which the time factor and slip line technology are introduced to realize the analysis and calculation from small deformation to large deformation, which is a comprehensive unification of the finite element method and discrete element method. Its commercial software currently circulating in the market is FLAC3D[19]. The discrete element method (DEM) was first proposed by Cundall and Strack[20] in the 1970s, which is to study the whole process of large deformation and deformation damage of geotechnical bodies by viewing them as discontinuous blocks. In the 1960s, the first national symposium on numerical calculation and model test of rock mechanics was held, and Wang Yongjia through the introduction of the basic principles of the Cundall discrete element method and the detailed explanation of the relevant real cases introduced the discrete element method into the field of geotechnical engineering in China for the first time, and opened the door to the numerical simulation and calculation of discrete element in China since then. Subsequently, the Chinese Academy of Sciences and Jidao Chengran Technology Company jointly developed the GDEM series of commercial software for mechanical analysis by using the discrete element method as the software base layer. Through eleven years of theoretical knowledge research and system development, Prof. Liu Chun and his scientific research team at Nanjing University independently developed a high-performance matrix discrete element simulation software MatDEM[21] based on the Matlab language, which adopts matrix discrete element computation method, and greatly improves the computation speed based on parallel computation of CPU and GPU, and expands the analysis process of a small number of particles to millions of discrete element numerical simulation units. The numerical simulation of millions of discrete elements has elevated the previous modeling theory from a purely small-scale schematic to a large-scale practical engineering field. This research result provides a new effective solution for the simulation of the landslide formation process. In this study, the discrete element method is used to simulate the landslide evolution process using MatDEM simulation software.

2. Inverted-pear-shaped Landslide

Zhuangzi's landslide overall shape in the plane is relatively rare, was approximately inverted pear-shaped, with the upper large and lower small. The back of the landslide is obvious in the overall chair-like terrain, consisting of several curved back walls with chair-like terrain, the back wall is 25-40m high, with a steeper slope of about 48°, and the upper part of the wall is covered with 5-8m thick Malan loess, which is mainly chalky, with large pore space development, containing a large number of plant roots. The lower part of the wall is covered with brick-red mudstone, and the continuity of the exposure is general. There is a landslide depression in the middle of the back wall of the landslide and the landslide body, and the depression is connected with the gully on the left side of the landslide body to form a terrain of big left and small right, which is presumed to be the result of the big displacement of the left side of the upper landslide body. The topography of the depression is characterized by an obvious anticlinal phenomenon. Slide surface overall back wall is steep, the central part is mostly gentle slopes, the front part of the terraces for the settlement was multi-level steep can extend to the foot of the slope, the longitudinal length of the slide body 860 ~ 880m, the width of the trailing edge can be up to 390m, the leading edge of the narrow, the narrowest place is less than 5m, the front of the slide body is mostly in the form of mud and stone flow piled up in the gully, the main direction of the main slide for 305 °, the height of the leading edge of 2706m, the height of the trailing edge of 2,858m, the relative difference in height of 152m, the average slope is only 10 °, the more longitudinal The average slope is only 10°, which is relatively gentle. The middle and rear part of the slide body also shows the characteristics of anticlinal terrain, which is the landslide depression produced by secondary sliding, even if these two terrains have been reclaimed and leveled manually in the later stage, the anticlinal phenomenon still exists obviously. The back wall of the landslide is continuous with the right wall of the landslide, with a longitudinal length of the right wall of 810-860m, a relative height difference of 2-6m, and a good continuity, with the upper part of the wall being a steep bank, connected to the middle part of the wall and the path, and the south side of the path is bounded by the steep bank and extends to the mouth of the gully. The upper right side of the boundary side helps rock and soil body stability is poor, and there are several small slip phenomena. The left boundary of the slide is bounded by steep cans, and the upper steep cans are connected to the back wall of the landslide, locally exposed brick-red mudstone of the Neo-Confucian system, with poor integrity and strong weathering. After the destabilization of the slide, the front part of the slide is piled up in the original gully, forming the phenomenon of direct contact between the slide and the terraces, and there are steep cans between the slide and the terraces, with a height difference of 3-5m, and the steep cans are mainly composed of the secondary terraces with obvious horizontal laminations. Part of the slide material along the gully was converted into mudflow into the Yangyong ditch and was taken away by the water. The lower part of the slide is now developing again the gully, the depth of the gully varies from 5 to 8m, the gully is narrower, the widest place is less than 5m, the length is larger, from the middle of the slide body extends to the foot of the slope, the lower part of the gully to the right side of the corner cutting terraces converge into the Yangyong ditch, more zig-zagging. The ditch helps exposed mudstone, sandstone, and loess extrusion mixed slide material, visible obvious rock and soil body extrusion damage phenomenon, the head of the ditch there are springs exposed. The left side of the front of the gully is the secondary terrace of Yangyonggou, and a stable secondary terrace stratum can be seen in the gully. According to the survey drilling, the thickness of the slide body is 11.3-29.0m, thin in the middle and upper part and thicker in the lower part, with a total volume of about $636.4\times10^4 m^3$, which is classified as a hauling-type medium-layer giant loess-mudstone mixed landslide according to the cause and scale.

3. Discrete Element Method

Many engineering examples and research problems in the field of geological and geotechnical engineering belong to the large deformation damage phenomenon, finite element based on its basic assumptions and principles, although it can simulate the small deformation and contact relationship and stress distribution state, it can not study the large deformation process of the geotechnical body well, but the numerical computation method of the discrete element can simulate the discrete medium and the large deformation simulation process effectively, and has a wide range of research significance and application value in the field of geological and geotechnical engineering and materials development, energy exploitation and other discrete body large deformation. Engineering and materials research and development, energy extraction, and other discrete body large deformation fields have a wide range of research significance and application value.

The idea of discrete element solution is to take the given discrete particulate units as a matrix of units, record the basic properties of the discrete units in the matrix, connect the particulate units one by one by using the principle of equivalent connection in combination with the actual material conditions, use the principle and the inter-unit forces and relative displacements as the basic solution variables, treat the positive and shear stresses as the positive and normal forces between the connection, and obtain the combined forces and moments between each unit and its neighboring units. The combined force and moment of each unit and its neighboring units in contact with each other are obtained, and then Newton's second law of motion is used to solve for the acceleration on each particle unit, and the velocity and displacement at the corresponding moment are obtained by integrating the time of the given unit, based on which the kinematic physical quantities such as the relevant velocity, acceleration, and angle of rotation of all the units can be obtained at any given moment.

The discrete element numerical simulation software MatDEM is used to construct a geotechnical body model close to the real one through a series of spherical particles stacked and cemented with specific physico-mechanical parameter indexes[22-23]. In the numerical simulation, by setting the fracturing effect, friction force, and damping force to convert the mechanical energy of the particle unit into thermal energy gradually during the movement process, all kinds of mechanical energy and thermal energy can be accurately calculated in this discrete element system, and the energy is conserved. In the numerical simulation, the mechanical energy is gradually converted into thermal energy by setting the fracture, friction, and damping forces to convert the mechanical energy into thermal energy during the motion of the particle unit, in which all kinds of mechanical energy and thermal energy can be accurately calculated in the discrete element system, and the energy is conserved (**Figure 1**).

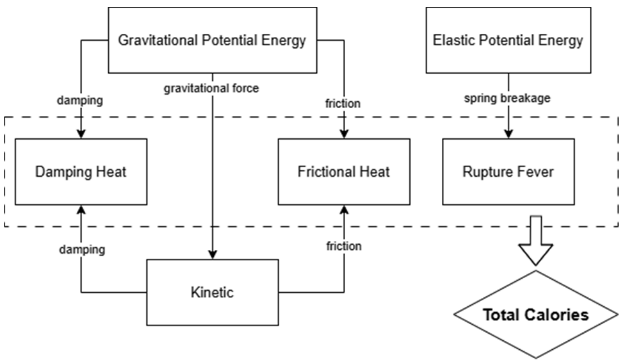

Figure 1. The whole process of landslide energy transformation

In the discrete element calculation process, the velocity displacement of the particle unit at a certain moment is determined by the time-step iterative calculation method. A traditional mechanical method is used to calculate the velocity of the particles at a certain moment in time, and the direction of the combined force of the particles is obtained through a mechanical contact model, which is divided by its mass to obtain the acceleration index. In an iterative time step, the average velocity is obtained from the initial velocity and the velocity at the end of the iteration, and the displacement index can be obtained by using the average velocity. Repeated iterations are used to realize the continuous dynamic simulation process of landslides.

4. Numerical Simulation of Landslides

4.1. Model Building

In the numerical simulation of landslides, the elevation of the data before and after the slide is the basis for the establishment of the geological model, and we carry out the corresponding pre-slide terrain reconstruction based on the existing data to recover the terrain of the landslide area roughly.

Firstly, the national geospatial information cloud system is used to download the local dem elevation data file, and then ArcGIS is used to process this elevation data. The downloaded tif file is imported into ArcMap, and then the latitude and longitude coordinates of the local landslide are used to crop the raster file after the crop is completed, the 3D Analyst tool in the map can be used to generate the contour tool of the raster surface to get the rough terrain elevation of the area. By observing the peripheral topographic line elevation data rules of the landslide, it can be seen that the slopes on both sides of the landslide are more complete, the regional contour lines are continuous, and there is a downward concave tendency only in the body of the landslide, so it can be deduced that the slopes of the landslide are more continuous before the sliding, and the terrain can be restored following the principle of one-side slopes. Through the restored topography map get the profile topography before not sliding (**Figure 2**) to establish a suitable two-dimensional discrete element model.

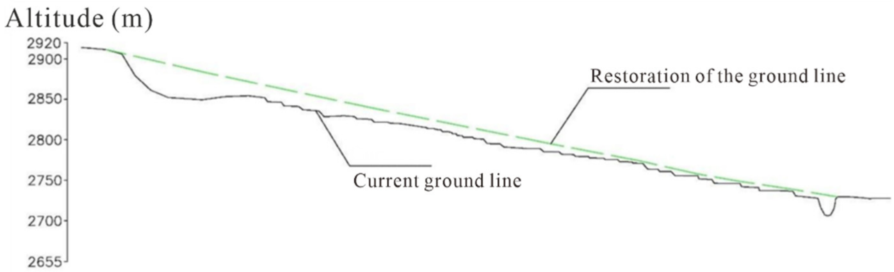

Figure 2. II-II profile terrain restoration

Then the command is used to establish an empty two-dimensional model box of 1000m×290m, and then the discrete element model is initially established by stacking particles in the model box, setting the radius of the particle unit in the model box to 0.5m, setting the particle size dispersion coefficient of the particle unit to 0.2, and simulating a total of 295126 units in the model box. The particle unit in the model box under the action of gravity to iteratively calculate the relative displacement that occurred, considering the actual situation of the geotechnical body not only has the action of gravity and a long period of consolidation, the use of compaction commands on the particles for compaction, and ultimately piled up in the model box.

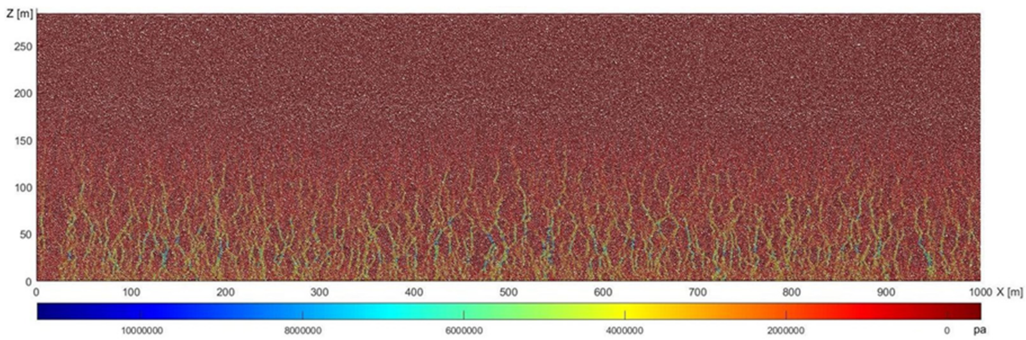

Figure 3. Stacking Model Z-Direction Stress

The deposition is completed to cut out the terrain and strata that need to be simulated, and the cut model is iteratively balanced for calculation. According to **Figure 3** and **Figure 4**, the positive stress of the particles in the vertical state is represented in the state of stress distribution, in the lower part of which the effect of the force chain can be seen, indicating that the accumulation state of the real strata under the action of geological camping force can be well simulated in the model construction.

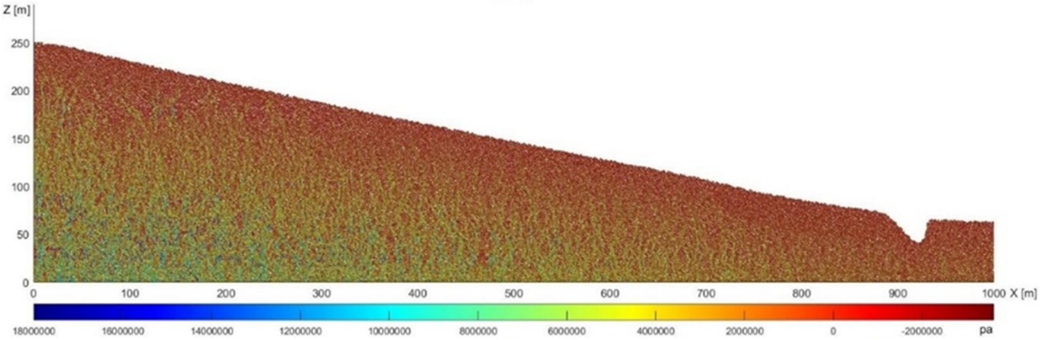

Figure 4. Positive Z-direction stress in the model after cutting

4.2. Numerical Simulation of Landslide Evolution

Through the field geological mapping and the aforementioned formation mechanism study, it was concluded that the Zhuangzi landslide was formed by multiple slides, based on which a two-dimensional profile was carried out to simulate the overall sliding of the landslide three times. In the initial original slope surface, the slope and the secondary terrace connection is complete, with time, the slope in the convergence of water forms a unified runoff, and slowly the terrace and the slope surface of the confluence of the deep gully, in the role of strong rainfall, the front part of the slope body part of the soil body physicomechanical properties of the deterioration of the first sliding in the state of the front edge of the proximity of the first sliding.

Since the specific formation time of this landslide is still unclear, it is not possible to accurately determine whether the sliding of this landslide was facilitated by earthquakes and other factors. The strength of the granular unit is assigned to the material under comprehensive consideration, and then the cementation between the slide body and the slide bed is disconnected to simulate that the front slide body is subjected to long-term scouring by the flowing water in the front and then slides along the weak surface of the soil-rock contact under the action of self-weight after softening. The calculation time step is 8×10^{-5}s, the total iteration is 2.75×10^{5} times, and the total simulation time is 22s.

When the first slide occurs, the landslide starts under the action of gravity, and the gravitational potential energy decreases, which is gradually converted into kinetic energy and thermal energy, and the kinetic energy is gradually converted into heat under the action of damping and friction, and consumed to 0. **Figure 5** shows the curve of the heat change of the first slide. The total mechanical potential energy of the first slide decreases by 5.4×10^{8}J, all of which is converted into thermal energy and kinetic energy, and the kinetic energy reaches a maximum of 6.3×10^{7}J at 6.4s and is finally and gradually converted into heat energy under the action of damping and friction. Among them, the friction heat is 4.4×10^{8}J which accounts for 81.5% of the total heat. In previous discrete element simulations of landslides, the heat generated by friction almost occupies a considerable proportion of the total heat[24], which results in a large amount of kinetic energy being converted into damping heat due to the damping effect of the leading edge terraces on the forward sliding body during the first sliding process.

Based on the model of the first sliding, it is assumed that the upper slope shear exit is exposed to be cut and adjusted to generate the model required for the second sliding. The calculation time step is 8×10^{-5}s, the total iteration is 8×10^{5} times, and the simulation lasts 64 s. After the first slide, the total energy in the model is cleared to zero, and the energy change of the slide is counted again, and the total reduction of gravitational potential energy is 2.47×10^9J, which is converted into thermal and kinetic energies, among which the kinetic energy reaches the maximum of 9.1×10^7J at 13 s, and is also converted into thermal energy. The kinetic energy reaches a maximum of 9.1×10^7J at 13s, which is also converted into heat energy. **Figure 6** shows that the friction heat is 2.3×10^9J, accounting for 93.1% of the total heat. In this sliding, the frictional heat is higher than the first sliding due to the larger sliding distance.

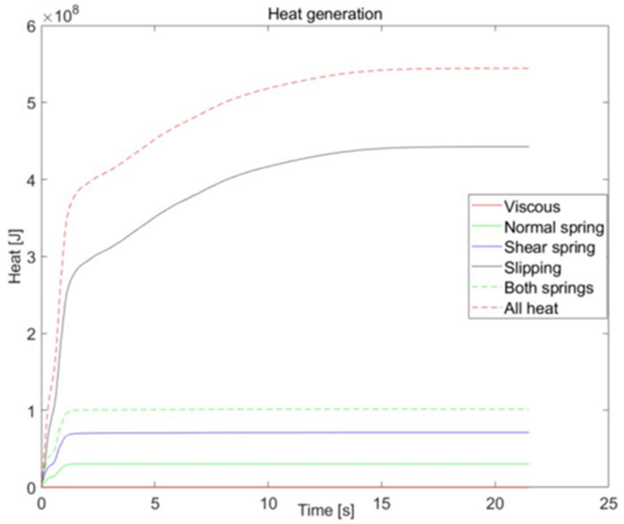

Figure 5. Heat change curve during the first slide

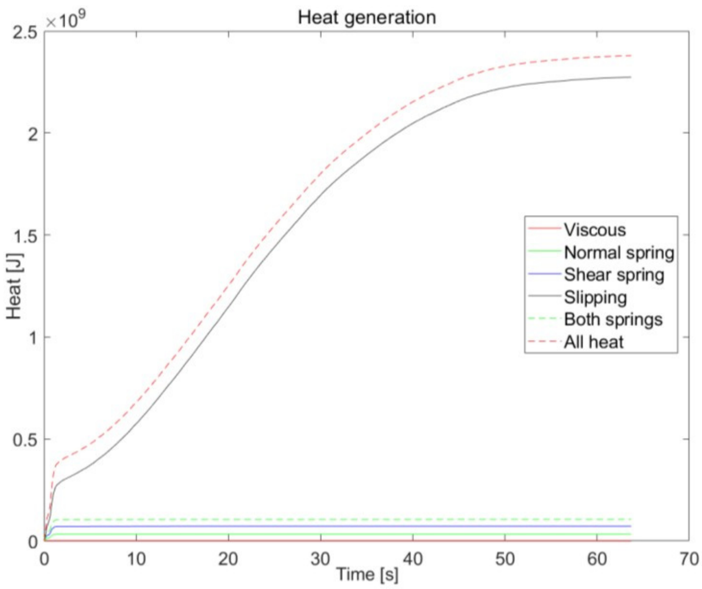

Figure 6. Curve of heat change during the second slide

The model after the second slide stops is cut again to simulate the process of the front part of the slide being taken away, considering the slide residual condition of the actual No.1 slide this time the cut particles are fewer, so it does not expose the shear exit. To explore the particle displacement when the slide occurs this slide will be a sliding slide body divided into two parts, which give the same micro-parameter indicators. The third slide was simulated under gravity by iteratively balancing and disconnecting the bond between the slide and the bed. The time step of this simulation is 8×10^{-5}s, the total iteration is 1.2×10^6 times, and the simulation lasts 96 s. The total reduction of mechanical potential energy is 1.15×10^{10}J, which is gradually converted into thermal energy and kinetic energy during the sliding process, among which the kinetic energy reaches the maximum of 4.59×10^8J in 36s, and then it is gradually dissipated in the form of heat. From Fig.7, it can be seen that the friction heat is 1.14×10^{10}J, accounting for 99.1% of the total heat.

5. Result

Comparing the maximum velocities at different moments during the three sliding processes, the first slide filled the gully at 8s, the velocity decreased rapidly under the obstruction of the secondary terrace at the leading edge, and the velocity of the surface particles gradually decreased, and finally stabilized. The maximum velocity of the second slide jumped around 23m/s from the beginning of the slide to 26s, which was mainly due to the friction in the sliding process and the hindering effect of the first residual slide on it. At 30, the re-flushed trench was filled and the maximum velocity started to decrease. After arriving in the trench, the particles in the surface layer of the slide increase in speed under the force of gravity the pulling effect of the front slide and the pushing effect of the rear slide, and the particles in the surface layer slide forward in the form of debris and finally stop.

Table 1. Three sliding volume heat statistics

Sliding area	Total volume (m^3)	Calorie (J)
One Slide	3449.5	5.4×10^{8}
Second Slip	2772.4	2.47×10^{9}
Third Slip	8116.8	1.15×10^{10}

According to the statistical results of the volume of sliding particles at each time (**Table 1**), it can be seen that the volume of the first sliding body that occurs is larger than that of the second sliding body, but its generation of inverted is smaller, which is due to the obstruction of sliding by the leading edge of the terraces, and the energy of the last two sliding shows a trend of growth. When the inverted pear shape develops upward its position farther and farther away from the gully, then the movement distance, speed, and energy will show an increasing trend. From the perspective of numerical simulation, it reflects that in the process of upward development of the gully, the scale of its subsequent landslides will also gradually increase, and gradually form this kind of upper large and lower small form. Using the numerical simulation method to invert the simulation of Zhuangzi landslide from the main slide direction, it is concluded that the mechanical mechanism of the landslide is traction type, and the displacement and energy of each slide at the trailing edge increase compared with the previous one, which is consistent with the destabilization mechanism obtained from the qualitative analysis.

6. Conclusion

In this study, the current remote sensing images and digital elevation maps of landslide were used to recover the topography of the pre-slide slope in a general inversion, based on which a two-dimensional landslide particle discrete element computational model was established by selecting the main slide profile of the landslide in conjunction with the engineering geological conditions of the landslide and the feasibility of the simulation. The specific conclusions drawn are as follows:

1. By scouring the leading edge to form a gully to produce the first sliding of the slope, this sliding is mainly dominated by the collapse of the leading edge, the trailing edge is a slow creeping trend.
2. The displacements of the three simulations of the landslide show a gradual increase, and the overall sliding displacements and velocities show a stratification trend from the surface

to the internal displacements gradually becoming smaller, which indicates the shear effect inside the slide in the process of sliding.

3. In the simulation process, the energy change of subsequent sliding will increase compared with the previous one, reflecting the trend of gradual expansion of the inverted pear-shaped landslide to the subsequent development.

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