Disaster control and effect evaluation of high and steep slope based on the landslide mass chain disaster model

XIE Lianku1,2, Cao Hui3*, YANG Tianhong2, WANG Zhixiu1, Yuan Ziqing1, JIANG Heguo4, YANG Zhengsong1
1. BGRIMM Technology Group, Beijing 102628, China; 2. School of Resources and Civil Engineering, Northeastern University, Shenyang, Liaoning 110819, China; 3. School of Civil and Resource Engineering, University of Science and Technology Beijing, Beijing 100083, China; 4. Yiliang Chihong Mining Co., Ltd., Zhaotong, Yunnan 657600, China

Abstract: According to the investigation on the distribution of surface geological hazards in Maoping Mine, Yunnan Province, the stability calculation and discrete element numerical simulation of Meitanyakou landslide were carried out. The result shows that under the action of earthquake and rainfall, the Meitanyaku landslide has a chain disaster mode of high source start-up, acceleration slippage on the steep slope, gentle slope debris flow scattering and accumulation, and block rolling and throwing. Based on this, the reinforcement and treatment scheme in the landslide source area was formulated: the surface soil and vegetation in the gentle slope area were used to block the landslide, the passive protective net was installed at the bottom, and the reinforcement and treatment facilities were monitored. Meanwhile, a complete set of advanced and reliable slope online monitoring and early warning systems was established. After treatment, there was no unstable landslide, and the slope and its engineering structures in the monitoring area were stable, which shows that the chain disaster mode of landslide geological disaster and the complementary scheme of prevention and control countermeasures are effective.

1. Introduction
China is one of the regions with the most severe landslides in Asia and even in the world. Significantly since the 1980s, with the rapid development of economic construction and the influence of natural factors, landslide disasters in China have increased year by year. Because of its wide range of instability, a large landslide disaster mass carries enormous potential energy when separated from the parent body, which often brings destructive damage and heavy casualties. Therefore, it has always been the focus of scholars and researchers at home and abroad. Wu et al. [1] pointed out that China faces many engineering geology and environmental problems in the 21st century, such as the dynamic stability of high and steep
slopes. Therefore, it is necessary to deepen theoretical research and develop engineering geology for solving these problems. Huang [2] pointed out that large landslides in China usually have complex formation mechanisms: sliding-cracking-shearing model, retaining wall collapse model, horizontal-pushing model in sub-horizontal strata, large-scale toppling model in reverse-dip strata, and the creep (bending)-shear model in bedding rock, etc. Zheng et al. [3,4] argued that the traditional quasi-static method and time history analysis method of safety factor have some limitations and put forward the dynamic time history analysis method and dynamic analysis method of strength reduction based on the tension-shear failure, which provides a new idea for the calculation of slope seismic safety factor. Shi et al. [5] proposed a popular numerical method in the 1990s based on the advantages of finite element method (FEM) and DDA method. Sun et al. [6–8] adopted the measures of cutting upper to mend the lower parts, pre-stressed anti-slide piles, anchor rod (cable) anchoring and slope protection, and spraying and greening methods for landslide disaster management, and achieved good comprehensive treatment effect. Yang et al. [9–11] proposed that progressive damage and failure of slope rock mass is the essential characteristic of slope rock mass instability precursor, and established a slope instability criterion based on microseismic precursor information and the strength reserve coefficient of the slope rock mass. However, due to many factors affecting landslides, it is of great theoretical and practical significance to carry out in-depth fundamental research on high and steep slope instability mechanism, sliding law, prevention and control countermeasures for effectively preventing and controlling slope landslide geological disasters, protecting the regional geological environment and promoting the development of slope disaster control technology.

In this paper, the Meitanyakou landslide mass in the earthquake-prone area is taken as the research object. The stability calculation check and numerical simulation analysis of the landslide mass, the instability mechanism, sliding characteristics, energy loss, and scattering range of the landslide mass are summarized. Finally, the overall scheme of prevention and control countermeasures for the high-level Meitanyakou landslide mass is formulated to prevent and control the surface mountain safety in Hedong District.

2. Investigation on the Meitanyakou landslide mass disaster

Meitanyakou slope is located in an earthquake-prone area, and the slope stability is affected by the earthquake, rainfall, terrain, stratum lithology and other factors. A local landslide occurred at the high-level Meitanyakou on the surface of the mining area on September 6, 2015, which seriously threatened the safety of personnel and property in the mine production area. The distribution of the landslide is shown in figure 1. Combined with the field investigation, it’s found that the Meitanyakou landslide mass is mainly composed of diluvial gravel and eluvium-deluvial gravel-bearing silty clay, with local clay, which has the following main characteristics:

(1) The landslide masses are irregularly distributed, mainly manifested as loose surface deposits and rock blocks sliding and rolling. The main sliding direction of the landslide mass is 288°, with a length of about 60m, a transverse width of about 40m and an average thickness of about 3m. The estimated volume of the landslide is 7200m³;

(2) The plane shape of the landslide mass is like a round-backed armchair, with apparent
cracks on the rear edge and an elevation of about 1503m. The boundaries on both sides are obvious, while the boundary on the front edge is not apparent due to sliding and collapse.

3) The deformation and failure of the landslide mass resulted in the formation of many tension cracks on the ground at the rear edge, and the length of the crack extension can reach about 20m, the maximum crack width can reach 20cm, and the landslide mass sinks about 2-5cm.

4) The landslide mass appears loose, with the central part with block stone having collapsed under the action of groundwater and its gravity, while the soil has been hollowed out under rainwater erosion and groundwater seepage so that the exposed block stone forms dangerous rock mass.

Figure 1. The distribution area and cracking failure of landslide disaster

3. Calculation check and analysis of stability characteristics of landslide mass

3.1 Parameters for stability analysis and calculation

When calculating the stability of the landslide mass in its intermittent creep state, the shear strength parameters $c$ and $\phi$ of the soil of the sliding zone should be taken combined with the laboratory test values and the inversion values, hence the mechanical parameters of the landslide mass are shown in Table 1.

| No. | Material                  | Volume weight $\gamma$(kN/m$^3$) | Cohesion $c$(kPa) | Internal friction angle $\phi$(°) | Remark                  |
|-----|---------------------------|----------------------------------|-------------------|----------------------------------|-------------------------|
|     |                           | Natural                        | Saturated        |                                  |                         |
| 1   | Soil of sliding mass      | 18.7                           | 19.4             | 36.3                             | 13.9                    | natural state           |
| 2   | Silty clay                |                                 |                   |                                  |                         | saturated quick shear   |
|     |                           | 16.8                           | 17.8             | 8.0                              | natural inversion value |
| 3   | Soil of sliding zone      |                                 |                   |                                  | recommended value       |
| 4   |                           | 16.8                           | 18.1             | 17.9                             | 8.1                     |                         |

3.2 Stability checking calculation of landslide mass

1) Working conditions for stability calculation

The landslide masses are mainly composed of silty clay with gravel, and the failure model is the overall sliding along the bedding plane. Given the geographical location and damage degree of the landslide mass, the landslide prevention and control engineering is set as grade
III, with its load combination including basic load and special load, which shall be calculated by the following four stability working conditions:

I Working condition – the natural state of self-weight. When calculating the remaining sliding force, take 1.15 as a safety factor;
II Working condition -- self-weight + groundwater. When calculating the remaining sliding force, take 1.15 as a safety factor;
III Working condition -- self-weight + continuous rainstorm + groundwater. Take 1.05 as a safety factor to check;
IV Working condition -- self-weight + earthquake + groundwater. Take 0.10g for earthquake, and safety factor as 1.05 to check.

2) Stability calculation and analysis
According to the analysis and arrangement of the survey data, the Meitanyakou landslide mass in the mining area mainly slides along the soil-rock contact surface. Therefore, the calculation and analysis are carried out based on the broken-line sliding surface, and the unbalanced thrust transfer coefficient method is used for the stability calculation. Based on the deformation characteristics of the landslide mass and the state of each landslide, the evaluation criteria for the stability of the landslide mass are as follows:

(1) $F_s < 1.0$, unstable;
(2) $1.0 < F_s < 1.05$, understable;
(3) $1.05 < F_s < 1.15$, basically stable;
(4) $F_s > 1.15$, stable.

Under different working conditions, the stability of the main section of the landslide mass is calculated according to the transfer coefficient method, with the calculation results as follows:

| Section No. | Calculation working conditions | Stability Coefficient $K_f$ | State of stability |
|-------------|--------------------------------|----------------------------|--------------------|
| I - I'       | I Working condition: self-weight | 1.027                      | understable        |
|              | II Working condition: self-weight + groundwater | 1.020                      | understable        |
|              | III Working condition: self-weight + rainstorm + groundwater | 0.996                      | unstable           |
|              | IV Working condition: self-weight + groundwater + earthquake | 0.981                      | unstable           |

From the stability coefficients of the landslide mass under different conditions, it can be seen that the landslide is understable under the conditions of its self-weight and groundwater, and it is unstable with one more the action of an earthquake. Therefore, groundwater, rainstorm, and earthquake have a significant influence on the stability of landslides.
Landslides are usually in an unstable state under the action of rainstorms and earthquakes. On the one hand, in the case of a rainstorm, the self-weight of the soil of sliding zone increases, the soil of the sliding zone is softened, and the shear strength parameters $c$ and $\phi$ decrease. On the other hand, the seismic force increased the sliding force of the landslide mass, which leads to the instability of the landslide mass. In conclusion, rainstorms and earthquakes are the main controlling factors of the stability of the whole landslide, which is consistent with that of the field investigation.

4. 3D numerical simulation analysis of the whole process of landslide under complex conditions

In history, a total of 146 earthquakes occurred in the study area. The seismic fortification intensity is $\text{Ⅶ}$, and the basic earthquake acceleration value is 0.10g. Since 2012, there has been a strengthening trend of regional tectonic activity, so the influence of main controlling factors as rainstorms and earthquakes needs to be taken into account when simulating the process of landslides.

4.1 Numerical calculation model

1) Establishment of the 3D numerical model of the landslide mass

The PFC$^{3D}$ $^{[12-14]}$ numerical model of the Meitanyakou landslide mass area has been established based on the geological and topographic features of the mine. The overall models of the slope and surface deposits are shown in figure 2. With comprehensively considering the computer performance and the reliability requirements of the model, it is determined to set the radius of the model sphere element as 1.5m. The total number of particles produced was 8317 with the particle model coefficient of 0.6 and initial contact strength of 1 MPa. The number of 3D wall elements is 79,430, the longitudinal and tangential stiffness of Wall takes $2.5\times10^{11}$ N/m, and the sliding model coefficient takes 0.7. The parallel bonded model is adopted (figure 3), in which the interaction between particles is produced in the form of contact force through internal inertia force, torque, etc. Based on this 3D numerical model, the failure mechanism, sliding model, energy loss, damage range and impact on the industrial site of the landslide under different combinations of gravity, rain and earthquake are analyzed emphatically.

![Figure 2. 3D numerical model of landslide mass with discrete element](image)

(a) 3D surface model  (b) Generation range of particle ball  (c) PFC$^{3D}$ model
2) Application method of water pressure

Regarding the application of water head conditions, it is mainly by controlling the height of the water head and generally controlling the sliding force of particles at different water head positions to simulate the instability of slope sliding caused by rainfall. In this simulation, the water pressure increases linearly with the change of the water head. When the rainfall increases, the water head increases accordingly. That is, the sliding force of the bottom particle unit increases.

3) Application method of seismic load

On September 7, 2012, earthquakes of magnitude 5.7 and 5.6 occurred successively in the mining area, with focal depths of 14km and 10km, respectively. The epicenter locating near the mining area, and the seismic waveform data provided by the local Seismological Bureau is shown in figure 4.
In the 3D landslide simulation process, the measured seismic load is directly applied to the Wall element as the rigid bedrock. Then, the motion law of rigid Wall is controlled by function. The rigid Wall rubs with particle element to transmit the seismic wave to the landslide mass element, and the landslide mass element moves under the action of the dynamic seismic wave. Finally, the potential landslide mass undergoes incubation, destruction and start-up, and landslide occurs, sliding from the landslide position to the pit bottom. The surface response and velocity vector distribution pattern are shown in figure 5.

Figure 5. Applied waveform and surface changes

4.2 Simulation analysis of landslide process under rainfall conditions

In this simulation, the water pressure increases linearly with the change of the water head. According to the geological model, the elevation of the highest point of the studied landslide area is about 1,740m, the bottom level of the slope is about 924m, with the elevation difference is about 816m. Therefore, the water level used in the simulation mainly refers to the elevation data, as shown in figure 6.

Figure 6. Sketch map of applied water head

The overall sliding trend model of the Meitanyakou landslide, under the conditions of self-weight and heavy rainfall, is analyzed as follows:

(1) The upper slope of the landslide area is steep, with a maximum slope of 75°, which may collapse first under the action of water saturation and gravity, and then slides down along the main sliding direction of the gully.

(2) There are steep slope areas with exposed bedrock and gentle slope areas with a large area and a large amount of green vegetation in the middle and lower part of the landslide area. The landslide mass may fall through the acceleration in the steep slope area under the action of gravity after rushing out of the front edge of the instability area. The sliding speed of the landslide mass decreases under the buffer of the quaternary topsoil and the blocking of tall trees and low shrubs, and a large number of them are spread and scattered in the lower part of the gentle area to form an accumulation body. As the landslide mass passes through the peaceful area, the vegetation on the surface will have the apparent mark of scratching and overwhelming. Although the front edge of the landslide mass is slightly impacted during the sliding process, it maintains the initial state of motion.
4.3 Simulation analysis of landslide process under earthquake

1) Bonding fracture and its typical characteristics

Comprehensively considering the effects of earthquakes, failure began to occur between the particles after the calculation of the model, and there was a total of 5,800 fractures. Since the initiation of the landslide, the particles have been affected by surface terrain, collisions, scratches, and other factors, increasing the internal force between particles in the rock body, gradually exceeding the bonding strength, resulting in the continuous failure of contact bonding and parallel bonding. Thus, 0-5,400 time-step is the period of rapid development of fractures; In the following 5,400-8,500 time-step, the fracture gradually entered a stable period; After the 8,500 time-step is the period of the debris flow stage, the fracture no longer occurs, and the particle movement shows an obvious slip state, as shown in figure 8.

Through the energy tracking of the entire system, the relationship between the kinetic energy, friction energy consumption, and potential energy (i.e., elevation change) of the landslide mass is analyzed for determining the energy changing curve of the entire landslide movement process, as shown in figure 9. By analyzing the simulation results, it can be seen that:

(1) When the landslide mass’s instability slippage starts and slips to the acceleration zone on steep slope (Zone B), the gravitational potential energy is continuously transformed into the kinetic energy of the landslide mass, and the collision between the rock bodies intensifies;

(2) When the landslide mass accelerates into the gentle slope accumulation area (area C), due to the reduction of the slope, the friction energy increases, and the kinetic energy is consumed sharply due to the blocking of Quaternary topsoil buffer and surface vegetation. As
a result, many landslide masses are scattered and accumulated below the gentle slope area.

(3) A small amount of the blocks enters the washdown zone (Zone D), the blocks collide with the gully and are blocked and buffered by the site so that the kinetic energy of the blocks gradually decreases, which are finally scattered and accumulated on the industrial site.

(4) During the sliding process of the landslide mass in Meitanyakou, the collision between rock bodies, the blocking of surface vegetation, and the buffering of the quaternary topsoil significantly consume the energy of the system, resulting in the reduction of the movement speed of the landslide mass and the change of the movement path, which has a significantly influence on the movement accumulation characteristic of the landslide mass.

Figure 9. Energy change curves

2) Analysis of movement mechanism of landslide mass

The original topography of the landslide area presents the topographic characteristics of "steep upper bedrock, gentle middle topsoil slope, and relative inclination lower." The burial depth of the bedrock in the middle of the landslide mass is significantly greater than that of the lower bedrock, and the landslide mass in the middle and lower parts does not entirely disintegrate after moving down as a whole. Instead, the landslide mass scattered and accumulated in the lower part of the peaceful area primarily after being accelerated and collided on the steep slope and buffered on the peaceful area. As a result, part of the block moves downwards at high speed, pushing and sliding to the center of the bottom channel.

Combined with the simulation calculation results (figure 10), it can be seen that when the calculation reaches 3,000 steps, part of the rock mass breaks and slides, and the front edge of the landslide mass begins to move downwards and hits the mountain first. When the calculation reaches 6,000, the shape of the entire landslide mass is deflected, that the movement direction is basically changed from the original westward to the southwestward. Meanwhile, the front edge of the landslide mass has slipped ahead, and the landslide mass has formed a triangular sliding state as a whole, scattering and accumulating along the gully below the area after being buffered by the surface soil of the gentle area and blocked by vegetation.
Comprehensive analysis shows that the high-level Meitanyakou landslide not only shows its unique sliding instability characteristics (such as the formation of the rear edge slip surface, the difference in the formation of the left and right sides of the edge, etc.) but also shows the movement characteristics of “emergency braking” of the landslide mass and multiple stacks of accumulation body. According to the various phenomena exhibited by the landslide movement, the landslide movement process can be summarized as high-level source start, acceleration slippage on a steep slope, debris flow scattering and accumulation on gentle slope, and blocks rolling and scattering on washdown zone. The movement mechanism can be summarized as the conceptual model shown in figure 11.

5. Comprehensive prevention and control technical plan and implementation effect of landslide disaster in Meitanyakou

5.1 Regionalization of landslide characteristics zone based on chain disaster Model

Due to the large area of the landslide and the different characteristics of each area, combined with the simulation analysis results and the actual characteristics of the landslide source development, movement process and accumulation distribution, the entire landslide mass can be divided into four characteristic zones: the landslide source zone (Zone A), acceleration zone on steep slope (Zone B), accumulation zone on gentle slope (Zone C), washdown zone (Zone D), as shown in figure 12.

1) Landslide source area

The landslide source zone refers to the position between the highest point of the steep wall at the rear edge of the landslide and the front edge of the landslide. The source zone of the
Meitanyakou landslide is fan-shaped in a plane. The elevation of the rear edge of the steep wall starts at 1,510m, and the elevation of the front edge is 1,460m, with a relative elevation difference of about 50m. The topography of the landslide source zone is steep, with an average slope of 38°. The landslide mass has a longitudinal length of 60m, a lateral width of 40m, an average thickness of about 3m, and a landslide volume of about 7,200m$^3$. A large number of tensioned ground fissures developed on the rear edge and both sides of the slope.

Figure 12. Characteristic zones of landslide mass

2) Acceleration zone on steep slope
After the landslide mass breaks away from the sliding surface and rushes out of the front edge, it accelerates along the steep slope zone under the action of gravity. The elevation of this zone ranges from 1,300 to 1,460m, with a length of about 140m, and an average slope of 50°. It is located between the front edge of the landslide and the exposed bedrock river ditch. The terrain in this zone is steep, the bedrock is exposed, and the decline of landslide mass accelerates after being transformed into a debris flow.

3) Accumulation zone on gentle slope
The elevation of the gentle zone ranges from 1,026 to 1,260m, with a length of about 350m and an average slope of about 30°. This zone covers the collapsed pit on the original surface, being relatively open. The surface comprises quaternary elluvium-deluvial, diluvial-gravel, gravel, clay, and humus, and well-developed vegetation and luxuriant trees. The landslide debris flow passes through the acceleration zone on a steep slope and then falls into the gentle zone faster.

4) Washdown zone
The elevation of this zone ranges from 910 to 1,020m, with a length of about 150m and an
average slope of 30 to 35°. As landslide debris continues to accumulate, a small amount of debris will rush out of the gentle zone and eventually fell into the industrial site due to the lack of barriers in this zone. However, discrete element analysis showed that very few parts of the debris continued to roll downwards, passing through the industrial site to the river's opposite bank, forming a thrust accumulation zone.

5.2 Comprehensive treatment and safety monitoring of landslide area

It has summarized the instability mechanism, slippage law, energy loss, and the scattering scope of the Meitanyakou landslide mass through the stability limit balance checking calculation and the discrete element numerical simulation analysis. Finally, the overall prevention and control countermeasures are formulated by reinforcement at the source area of the landslide, making much greater use of the natural barrier effect of the surface soil and vegetation in the gentle zone, and conducting the online monitoring of the reinforcement facilities.

1) Reinforcement plan for landslide area

Given the state of the landslide area, it is necessary to strengthen the reinforcement of the landslide source area and make full use of the natural barrier effect of topsoil vegetation in the gentle slope area. Moreover, a comprehensive treatment scheme was proposed based on multiple measures of “pile-slab wall + clearing + interception & drainage ditch + water discharge + fissure filling”: Set up anti-slide pile-slab walls in the middle and front edge of the landslide; adopt the clearing model to remove the front-edge block stones, build interception and drainage ditch around the landslide, conduct water discharge to the landslide simultaneously as well as fill up the tension cracks on the upper surface, and install the passive net at the bottom.

2) Online monitoring and early warning system for landslide area

Geological disaster monitoring focuses on the surface displacement of the mining area. In response to the characteristics of landslides and treatment projects in the Meitanyakou area, an online monitoring system focusing on the displacement of the surface slope and retaining wall's surface was developed, as shown in figure 13. This system adopts a combined method of online safety monitoring as the central and manual safety monitoring as a supplement and intensively adopts the new long-distance intelligent total station for large-scale online monitoring.

Figure 13. Safety monitoring and data acquisition system of Meitanyakou slope
In order to evaluate the actual effect of the landslide treatment project, the monitoring data of representative surface displacement monitoring points in the Meitanyakou area were selected for analysis. From November 4, 2018 to October 13, 2019, the monitoring curve of the measurement point with maximum displacement change is shown in figure 14. It can be seen that the cumulative maximum displacement value of the landslide monitoring area is only 25mm, and the changing trend of each measurement point all tends to be stable, indicating that the overall stability of the landslide area becomes better after treatment. Therefore, identifying the chain instability model of the landslide mass and its treatment countermeasures are relatively effective.

![Figure 14. Displacement curve of process monitored in landslide treatment area](image)

6. Conclusion

Based on the investigation of the distribution of surface geological disasters, the stability calculation of the landslide, and the discrete element numerical simulation analysis, this paper proposes that the Meitanyakou landslide has a chain disaster mode of high source start-up, acceleration slippage on the steep slope, gentle slope debris flow scattering and accumulation, and block rolling and throwing. Furthermore, the reinforcement treatment, monitoring, and early warning project in the landslide area are carried out. The specific conclusions are as follows:

(1) The current disasters distribution in the mining area shows that topography, stratum lithology, rainfall, and earthquakes are the main factors for surface landslides. It can be seen, from the stability coefficients of the landslide mass under different working conditions, that the Meitanyakou landslide mass is understable under its weight and the groundwater condition and unstable under the action of earthquakes. Heavy rain and earthquakes are determined as the main controlling factors for the stability of the landslide. The calculation and analysis results are consistent with the on-site investigation results.

(2) The PFC3D model of the Meitanyakou landslide in the mining area with the discrete element numerical analysis software was established. Based on the simulation analysis, the landslide process is divided into four stages under the combined action of the earthquake and heavy rainfall, including: earthquake and rainfall-induced landslide mass start-up stage; stage of slip-collision acceleration of debris flow on the steep slope; debris flow scattering and accumulated stage, affected by surface soil buffering and vegetation blocking in the gentle slope zone; stage of little rolling down and scattering.

(3) Considering the stability, slippage model, energy loss, and scattering range of the Meitanyakou landslide mass, the overall scheme is proposed to strengthen treatment in the landslide source zone, make good use of the natural barrier effect of the surface soil and vegetation in the gentle zone, and monitor the reinforcement treatment facilities, with the
specific plan as follows:

- Set up anti-slide pile-slab walls in the middle and front edge of the landslide mass, clearing front-edge blocks.
- Conduct water discharge to the landslide.
- Build interception and drainage ditches around.
- Fill up tension cracks on the upper surface.
- Install the passive net.

(4) Finally, a complete set of advanced and reliable online slope monitoring and early warning systems has been established to effectively monitor the affected area's landslide and the reinforcement and treatment engineering structure. It can be seen that the rock mass in the monitoring area has not been displaced, and the slope and its engineering structures in this area are in a stable state, which also shows that the identification of the chain instability model of the landslide mass and the treatment measures are accurate and effective.

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