Failure mechanism and slip characteristics of landslides on loess plateau by continuous-discontinuous method: A case study

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ABSTRACT: This study focuses on the disaster-causing mechanism and sliding characteristics of sudden deep landslides in the loess area of Xiangning county of China. The continuous-discontinuous element method is employed to simulate the overall process of landslides from deformation accumulation to rupture and slip. The results show that the weak out-dip interlayer formed by long-term rainfall infiltration contributes to the landslides. The weak interlayer cannot provide sufficient anti-sliding force. Additionally, the soils at the leading edge exhibit a clear tendency of slipping at the beginning, and the mechanical process of landslide failure is shear-compression on the foot of the slope, shear in the middle, and pull crack at the trailing edge. During the sliding, the trailing edge sliding body obviously lags behind the leading edge sliding body. Finally, it is found that the numerical predictions are good in agreement with the field survey information of the loess landslides.

Keywords: Landslides, Continuous-Discontinuous Method, Failure Mechanism, Slope Stability.

1 INTRODUCTION

With the development of urbanization construction, the contradiction between people and land in the loess plateau of western Shanxi is prominent. The top of loess slope is formed in the terrain of beams, plateaus, and hills, and the buildings on the foot of slope are denser. Once a landslide disaster occurs, it will have a major impact to people's life and property safety. Thus the research and management of landslides face a great challenging.

Recently, with the rapid development of computer technology, numerical simulation has become an important tool in landslides research because of its low cost, high efficiency, intuitive and reliable calculation results. Numerical methods have been widely used in slope stability analysis currently. For example, Li et al. (2022) based on Darcy's Law and the law of conservation of mass, by ABAQUS, focusing on the analysis of the deformation of waste dump slope and the change character of safety factor under different rainfall schemes. Panda et al. (2022) used 3D modeling and FLAC3D to explore the influence of the annual groundwater level (GWT) on the Kotropi landslides. Kveldsvik et al. (2009) examined the potential danger zones of the KNOS rock slope and used the universal discrete element code (UDEC) for stability analysis, and analyzed the influence of slope crack geometry, crack friction, and groundwater conditions on slope stability. Combined the detailed field investigation with the laboratory experiments, Chang et al. (2021) used particle flow code (PFC) to study the instability and failure process of a loess landslide under strong motion.

Currently, there are few studies on the disaster-causing mechanism and motion characteristics of sudden deep landslides through the continuous-discontinuous method. In this work, taking the Xiangning "3.15" mountain landslides as an example, the continuous-discontinuous method (S. H. Li, & Rao, 2004) combined with the field investigation data is employed to analyze the causes of such landslides. The mechanical mechanism of failure, instability, and sliding motion of Xiangning "3.15" landslides are carefully analyzed, which can be benefit to risk assessment of many similar slopes in the loess plateau of western Shanxi.

2 ENGINEERING GEOLOGY OF THE SLOPE

The loess slope is located on the loess area at the southern end of Luliang mountain in the loess plateau of western Shanxi Province (Figure.1a). The mountains and rivers in the county are dense, the gullies are vertical and horizontal, and the population is densely populated (Figure.1b). Most of the residential houses are built on the slope on both sides of the beam, hill, tableland, and gully. On March 15, 2019, the "3.15" landslide in Xiangning occurred on the north side of Zaoling Township Health Center in Xiangning county, located on the loess residual tableland, and on the south slope of the nearly east-west "V" shaped loess gully. The disaster is sudden and strongly destructive, resulting in a total of 20 people killed. It is one of the most serious geological disasters in the loess plateau of western Shanxi in the recent years (Zhao & Zhao, 2020).

The original slope type is a slightly north convex steep slope with a maximum height difference of about 70 m and an average slope of 45° (Figure.1c). The landslides are in the shape of a round chair, and the main sliding direction is 340° northwest. Landslides form a slope of about 34°. Landslide thickness of 3-28m, an average of 14m, the leading edge of the landslide fan-shaped accumulation in the valley, east-west length of 154m, the maximum thickness of 20m, is a small-deep landslide (Figure.1d).

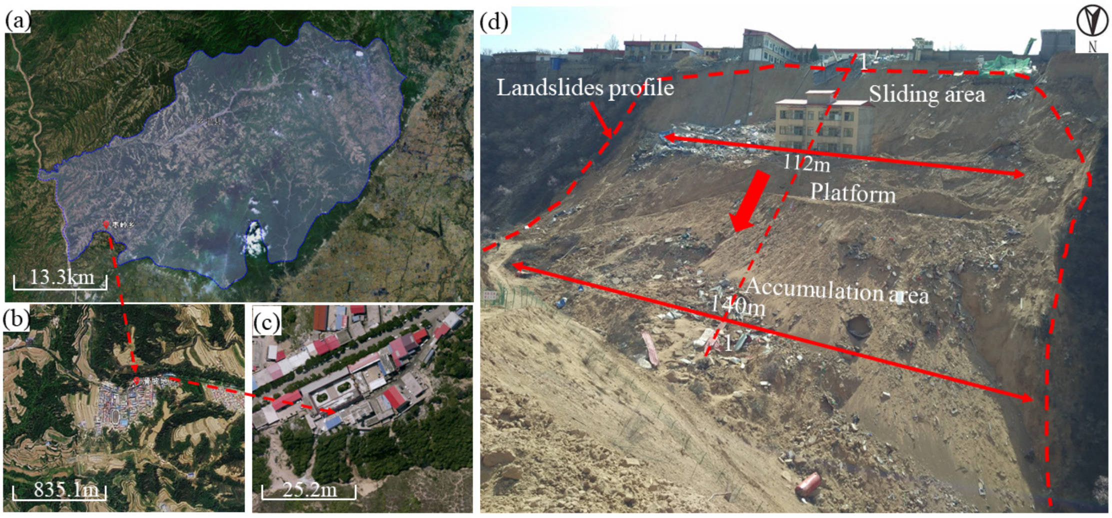


Figure 1. Location and profile of the landslides.

Detailed geological exploration was carried out in the study area. The rock and soil bodies within 52 m revealed by drilling in the exploration area are divided into three categories: filling soil (Q4ml), Malan loess (Q3eol), and Lishi loess (Q2pl). The geological profile of the landslides is shown in Figure 3. The soil mechanical properties of the laboratory tests are shown in Table 1.

Before sliding of the slope, the climate was very dry at that time, and there was no impact of earthquake and human activities. According to the field geological exploration data, the main reason for the instability of Xiangning landslides is the development of vertical joints of Malan loess on the upper layer of the slope, and the formation of highly saturated extraverted weak interlayer above the relative impermeable layer formed by the long-term vertical infiltration of the stable and uniformly distributed ancient soil layer silty clay. In addition, the original terrain of the landslide area is steep, and the three faces are slightly convex to the north. In the long-term geological evolution, the anti-sliding shear force provided by the weak interlayer is difficult to resist the slope sliding, and finally the sliding mass is sheared out along the weak structural plane to form a landslide under the action of its own weight. In addition, in mid-March, the study area is in the freeze-thaw period soil thawing soil-structure damage, while providing water for infiltration, which aggravates the slope instability to a certain extent.

In general, it is believed that the Xiangning landslides is a deep bedding landslide formed under the long-term geological evolution of loess characteristics and natural conditions.

3 NUMERICAL SIMULATION OF LANDSLIDES

3.1 CDEM model and constitutive selection

In this study, it is assumed that the soil layers are evenly distributed and the original topography of the slope is reasonably simplified. At the same time, to take into account the calculation accuracy and efficiency, mesh refinement is carried out in the potentially sliding body area, and the total of 54368 grids is generated for the slope model. The bottom of the slope is fully constrained, and normal constraints are applied on both sides of the horizontal direction. The corresponding measuring points are arranged at the typical position of the sliding body, and the displacement and velocity of the block at this position are monitored in real-time. The landslide model and measuring point distribution are given in Figure 2.

The deformation process of the slope is mainly divided into the elastic-plastic stage and the unstable sliding stage. Before sliding, the Mohr-Coulomb constitutive model is used to calculate and analyze the deformation accumulation and plastic failure expansion process of the slope geological body. After the instability and slip of the sliding body, considering that the relative deformation of the soil particles in the sliding body is much smaller than the slip displacement of the sliding body during the instability and slip stage. The linear elastic constitutive model is adopted for the soil inside the sliding body. Considering the sliding and fracture of the sliding body structural plane during the instability and failure process, the brittle fracture constitutive model and the Mohr-Coulomb failure criterion are adopted (Li, Wang, & Liang, 2015).

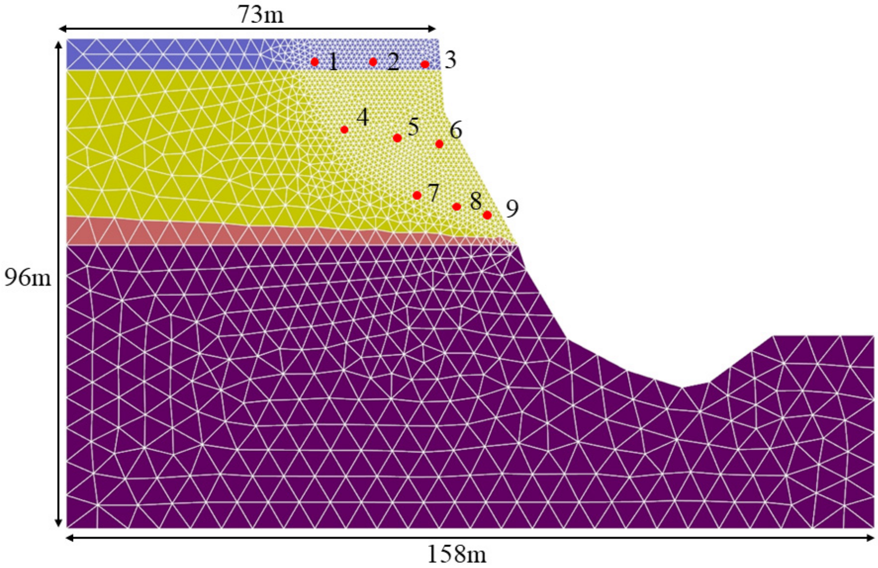


Figure 2. Model mesh and measurement points.

Table 1. The properties of soils.

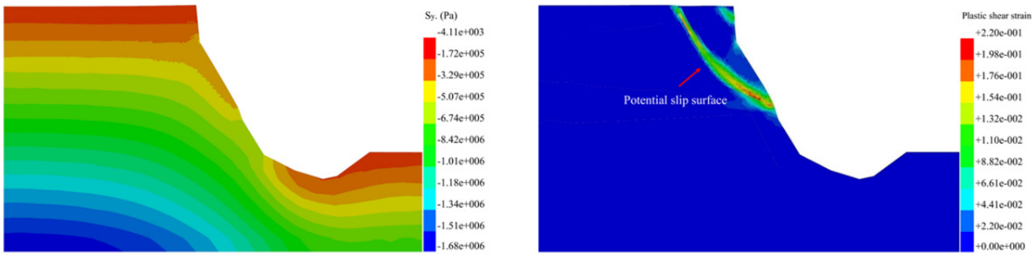
Mechanical properties		Miscellaneous fill	Malan loess	Weak intercalation	Lishi loess
Weight	[kN·m^{-3}]	16.5	17.8	19.2	18.5
Cohesion	[kPa]	5.0	38.2	33.2	41.1
Frictional angle	[°]	12.1	35.5	10.6	34.5
Young's modulus	[MPa]	6	13	10	16
Poisson's ratio	[-]	0.25	0.35	0.35	0.35

3.2 Analysis of the calculation results

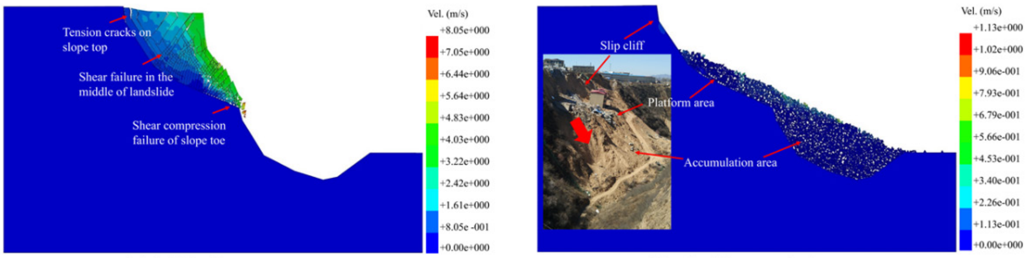
Landslide failure is a complex and long-term geological phenomenon. From deformation accumulation to fracture slip, there exists a typical process from qualitative to quantitative change accumulation. The deformation accumulation process of the Xiangning landslides is studied in the elastoplastic stage. Firstly, the slope model is solved to be stable in the natural state (only considering the self-weight effect), and the initial underground stress field of the slope is obtained as shown in Figure 3(a). After that, the displacement is cleared and the slope top building is considered to apply a 30kPa overload at the top of the slope for the plastic phase calculation to stabilize.

From Figure 3, it is noted that when the plastic stage is evolved for 1s, the shear creep failure of the slope is the first to occur in the soft interlayer and the soil at the upper slope surface under the action of self-weight; when the plastic stage is evolved for 2s, the plastic shear failure zone appears at the weak layer, and the landslides shear outlet position is determined, and the plastic failure zone develops to the middle locking segment with a typical progressive failure trend. When the plastic stage is evolved for 4s, the plastic deformation develops from the inside of the sliding body to the top of the slope and finally forms an arc-shaped plastic failure penetration zone, i.e., the potential slip zone has been formed, and the slope stability is difficult to be guaranteed.

At this instability moment, the deformation and displacement of the sliding body show the variation characters of the traction landslides, which means that the sliding bed is in a stable state, the sliding body exhibits an overall sliding trend along the potential sliding surface. However, the displacement of the leading edge of the sliding body is significantly larger than that of the trailing edge of the landslides. The slope soils produce shear creep deformation in the direction of the free surface, and the soil at the foot of the slope presents an obvious shear trend along the direction of the weak layer.



(a) Initial geo-stress field (b) Plastic zone distribution



(c) Initial slip state (d) Stacking completion status

Figure 3. The failure evolution process of the landslides by CDEM method.

In general, under the action of self-weight load, the slope shear creeps failure along the weak face to the front of the slope, and the shallow slope of the front edge of the slope has obvious displacement and velocity changes, resulting in the tension stress concentration of the trailing edge slope, the shear stress concentration of the locking section, and the shear stress concentration on the foot of the slope. At the same time, the upper soils of the trailing edge of the slope produce multi-level tension cracks, the staggered shear cracks of the locking section are developed, and the local fracture at the foot of the slope occurs, while the sliding body cracks and disintegrates, and slides downward. After the completion of the accumulation of the leading edge soil, a new free surface appears, and the trailing edge tensile cracks continue to develop deeper. The mechanical mechanism of deformation and failure is manifested as shear compression at the foot of the slope, shear in the slope, and tension at the top of the slope. From the displacement contours combined with field investigation, it is obtained that the slip motion is consistent with the actual deformation of the accumulation form.

By analyzing the change characters of both displacement and velocity at the monitoring points in the slip stage, it is found that the velocities and displacements of 9 monitoring points exhibit three typical change trends (three categories, (3, 6, 9), (2, 5, 8), and (1, 4, 7), see Figure 2), which correspond to the movement characteristics of the sliding body at three levels of the leading edge, middle layer, and trailing edge of the sliding body, respectively. To observe the fracture slip process more intuitively on the thorough, the displacement and velocity results of the three groups of measuring points from the leading edge to the trailing edge of the sliding body are averaged, which are shown in Figure 4.

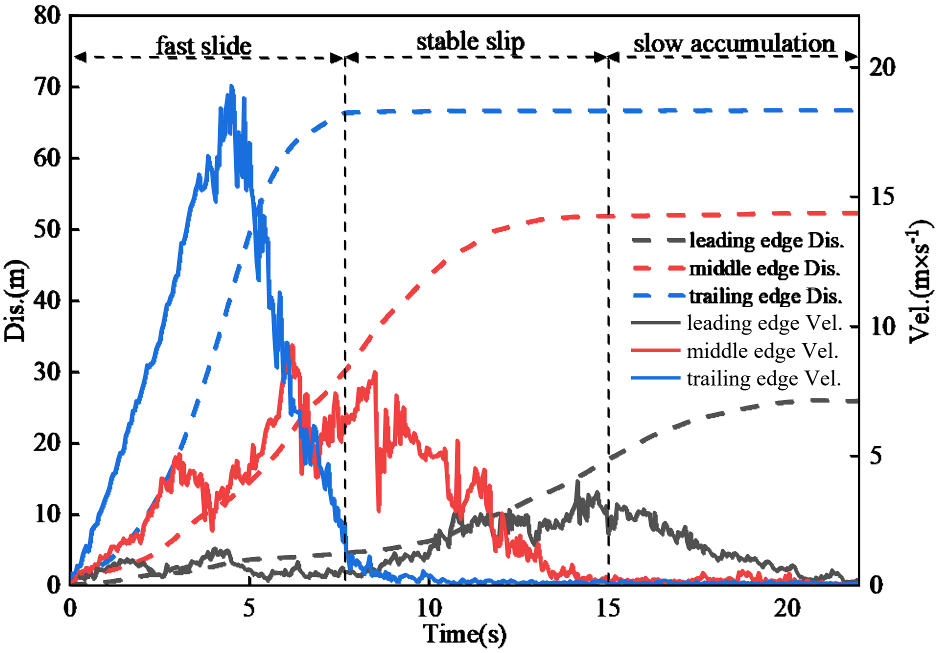


Figure 4. The average displacement and velocity histories of the sliding bodies.

It can be seen from Figure 4 that there are obvious uncoordinated movement characteristics in the process of landslide fracture and slip. The leading edge sliding body first slips and falls rapidly, and then the movement slip trend continues to develop to the deep trailing edge of the sliding body. Due to the anti-sliding force constraint of the leading edge soil and the inhibitory effect after accumulation, the movement of the middle and trailing edge sliding body has obvious hysteresis. The velocity and displacement peaks from the leading edge to the trailing edge show a typical step-type decline, which is in line with the typical stage movement characteristics of the sliding body from rapid fall-collision accumulation-slow accumulation. The numerical results of the measuring points are basically the same as the slip accumulation pattern in the above figure and hold a certain correspondence with the field situation. It is considered that the displacement and velocity changes of the typical measuring points can effectively reflect the sliding characteristics of the sliding body.

4 CONCLUSION

Based on the detailed analysis of the field survey and drilling results, Xiangning landslides are believed that the major cause of the landslides is that the original slope topography and long-term rainfall infiltration form a weak interlayer.

The whole process of landslides is simulated by the CDEM method. It is considered that the plastic failure of the slope starts from the weak interlayer and the steep slope surface and continues to develop to the trailing edge to form a potential sliding surface. The mechanical mechanism of slope failure and slip is shear compression on the slope toe-shear in the slope-tension on the top of the slope.

Through the analysis of the velocity and displacement results of the measuring points, it is considered that the landslide movement process shows the characteristics of rapid decline in the early phase, collision stoppage in the middle phase, and slow accumulation in the later one. The trailing edge of the sliding body evidently lags behind the front sliding body, which conforms to the motion characteristics of the traction landslides.

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