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Review Article

# Advances in the Study of Loess Flow Slides and Effects of the Coupling of Water and Gravity Erosion in Chinese Loess Plateau

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## Abstract

Loess flow slides can have catastrophic consequences and have therefore become a critical research topic in engineering geology. Recent occurrences have revealed severe problems in the prevention of these events due to imperfect understanding of effects of water and gravity erosion and how these factors can intensify a loess flow slide. In this study, we reviewed studies on the effects of water and gravity erosion with particular focus on three aspects: the erosion resistance of loess landslide deposits and the sliding mechanism of loess flow slides, effects of water and gravity erosion to intensify loess flow slide and its damage mechanism, and the loess land flow slide disaster mechanism and prediction methods. Additionally, landslide initiation and movement mechanisms of the loess flow slides that occur at the interface between loess and underlying mud stone are discussed. Three typical loess landslides caused by static liquefaction were used as examples and their possible pore pressure generation modes were proposed. It is recommended that characteristics of the basin (watershed), critical zone (tableland edge), and the dynamic variation of underground water level should be included in the comprehensive evaluation of the potential contributions of the different position and intensity of water and gravity erosion to loess flow slide events.

**Keywords:** Water and Gravity Erosion; Loess Flow Slide; Research Progress; Prospect

## Introduction

The loess area has long been a critical area of interaction between human and nature in north China [1]. The loess sediments record the history of environmental change and the civilization and provide a valuable reference focus of past environmental changes allowing prediction of future trends [2]. The loess plateau is one of the most vulnerable areas, with serious soil erosion and a delicate ecological environment, but is also a typical area used in arid and semi-arid farming and animal husbandry and provides an important energy and chemical base for China [3]. Additionally, it is the core area of the implementation of the Belt and Road (abbreviated B and R) strategic layout. Which also known as One Belt, One Road (abbreviated OBOR) or the Belt and Road Initiative is a development strategy and framework, that focuses on connectivity and cooperation among countries primarily between the People's Republic of China and the rest of Eurasia [4].

The loess plateau is the youngest growing plateau in the world and is the major strategic area of development in west China. This region makes up 1/20 of the land area in China and 1/5 of the cultivated land area. With more than 700 important cities in the region, it is home to 1/6 of the country's population and has important oil, gas and coal resources. The exploitation of energy and minerals and urbanization construction increases the risk of new loess disasters in this region [5].

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Landslides are one of the most common geological disasters in the Loess Plateau, and can cause traffic congestion, damage to housing and infrastructure, and can result in serious losses of life and property. For example, the famous Italian landslide in 1963 caused the death of more than 1925 people. In 2005, the Philippines landslide disaster killed more than 1800 people. The Tibetan Yigongcangbu high-speed landslides killed 30 people in 2000, with approximately fifty thousand people left homeless. A mountain landslide in Dongxiang County in Gansu province destroyed four villages and killed more than 250 people in 1983. In 2003, the famous Qianjiangping landslide, in the Sanxia Reservoir Area near the Yangtze River, blocked river flow for many hours, resulting in a huge lake and thousands of people left homeless [6].

Loess flowslide has attracted increasing attention because of its short duration and wide range of threats. In the Southern Tableland (Nanyuan) of Jingyang County, Shaanxi Province, China, loess landslides often occur along the slope of the tableland, causing heavy casualties and serious economic losses [7]. By the end of 1993, there were 40 flow slides with sliding mass of about 10 million m3, including a volume of over 300 thousand m3 for 19 landslides that killed 26 people, injured 30 people, and destroyed 300 cave-houses, and more than 2500 acres of farmland, for direct economic losses of nearly ten million Yuan. Thus, loess landslide disasters can seriously affect the local economy [8].

If large-scales landslides continuously occurring in loess platform margin area, easily lead to intensive Loess flow slide group. Such as the landslide group on both sides of Qingshui River in Sanyuan County, Shaanxi Province, Heifangtai landslide group in Yongjing County, Gansu province. Between 1992 and 1995, there occurs this landslide more than 50 times only on 10 km long Heifangtai table edge, cause great losses. One of landslides killed 5 people with four people seriously injured and 10 people slightly injured. Additionally, there was a direct economic loss of 15 million yuan, with 109 people forced to relocate, and a loss of 90 $hm^2$ of farmland. In there, roads were blocked for more than 20 days, there was destruction of water conservancy facilities, and other losses including fruit trees amounted to hundreds of millions of Yuan. Since 1995 to 2015, the occurrence of landslides has resulted in a loss of 0.8 $km^2$ of the total area of the original Heifangtai tableland [9]. There is an estimate that the loess plateau has lost precious flat area of 5 $km^2$ per year, for a direct economic loss of 1 billion Yuan or more [9]. The best way to protect the lives of people who live in these areas and the best strategies for the prevention and control of landslide disasters remain urgent problems to address [10].

**Figure 1**: The Potential Chain Loess Flowslide Group Along The Gully Side Wall [11].

There are several published studies concerning loess landslide characteristics, formation mechanism, movement mechanism, stability evaluation, and ideas for prevention and control measures [11-15]. However, there have been relatively few studies that investigate how intensive water and gravity erosion interact with each other to induce loess flow slides and affect the landscape. The developments of geologic environment, causes, movement process, movement mechanism, and disasters-causing characteristics of loess flow slides can contribute to the development and severity of landslides and the resulting debris flow. Loess flow slides exhibits characteristics of landslides and characteristics of soil flow. A landslide triggered by heavy rains will show some characteristics of loess soil flow, and depending on the perspective of the research, the same event may be studied as a slide or as soil flow. Indeed, there are even multiple names for this kind of event, as it can be referred to as a plasticity flow type landslide, a flow slide, or loess flow. Overall, there is a lack of consensus in the literature about the characteristics and properties of this kind of geological disaster [11]. There are many inducing factors of loess flow slides, including earthquake and rainfall. Average annual loess flow slides disasters have happened in recent years, and more than 80% of these occurred in the 5 to 9 months of the rainy season. During this time, the surface water has an increased load of soil, and groundwater weakens the sliding resistance of soil and increases the lubrication of the sliding surface. The potential loess flowslide group is widely distributed in the loess plateau. This kind of landslide group usually occurs in the quaternary system and has been subjected to shallow weathering accumulation, especially in the loess gully region (see figure 1). The effect of water and gravity erosion on loess flowslide is mainly concentrated in the water erosion on the slope surface and the water infiltration of slope rock mass weakening the shear strength and the lubrication of the sliding surface. The addition of gravity erosion to these processes can induce loess flowslide disasters. In the loess plateau area, after significant coupling effects of water and gravity erosion, the slope can easily internally crack or partially collapse occur, a first step to a loess flowslide disaster. Overall, imperfect understanding of the mechanism of geo-hazards induced by loess flowslide remains a widespread and long-term engineering geological problem [16].

Most of the loess plateau has significant erosion. To understand what happens during a loess flowslide disaster, it is important to study soil erosion. The erosion rate and floods will affect loess stability. The amount and behaviour of water and soil loss in this region has been greatly affected by human activities. The influence of human activity in this environment and how to avoid an increase in the instability in the loess region in the pursuit of continued development and production is an important research problem.

Loess is widely distributed in the world, accounting for 1/10 of the global land area. In Europe and North America, the northern boundary is roughly connected with the southern boundary of the Pleistocene continental glaciers, and is distributed in the United States, Canada, Germany, France, Belgium, the Netherlands, Central and Eastern European countries, the Soviet Union, Belarus and Ukraine; and in Asia and South America, it is adjacent to the desert and the Gobi. It is mainly distributed in China, Iran, Central Asia of the Soviet Union, Argentina, and in North Africa and New Zealand and Australia in the Southern Hemisphere, loess is scattered. Although there have been significant advancements in the study of the loess plateau environment and loess flowslide disasters, much remains unclear. In particular, the contribution of coupled water and gravity erosion effects on loess flowside events are poorly understood. The difficulty in forecasting and preventing loess flow slides requires comprehensive analysis of the mechanisms involved in loess flowslide based on different geological types, different disaster degrees, and different inducing conditions. Overall, understanding the action of the water and gravity erosion coupling effect in loess stability has important scientific value and strategic significance to building a regional early warning system for disaster reduction and prevention. These efforts are essential to safeguard regional security and to promote sustainable development.

## Methods

According to satellite imagery, the geological disasters of loess landslides were investigated on a macroscopic scale. On this basis, a field survey was conducted to analyse the effects of water and gravity erosion on loess landslides. Combined with relevant literature for analysis, the formation mechanism of loess landslide is identified.

## Results and Analysis

### Studies of the aggravation of loess flowslide by water and gravity erosion

Loess is sensitive to water. The shear strength of loess at the foot of slope decreases under the action of hydraulic and gravity erosion, which leads to loess landslide. Loess flow slides are one of the most widely distributed and the frequent types of geological disasters that occur in the northwest loess area. Scholars have done a lot of research from different perspectives. Terzaghi., *et al*. [12] showed that the production of pore water pressure and water weakening are important causes of induced landslides. Based on the results of a field landslide simulation experiment, Hatchinson [13] and Sassa [14] proposed a landslide occurrence mechanism of destroyed structure of the loess together with an increase in pore pressure, followed by liquefaction. They also pointed out that excess pore water pressure can cause a slide when saturation is greater than 85%. According to the *in-situ* field measurements and experimental data, Jiading and Yanghe [17] proposed the concept of creeping motion of saturated loess liquefaction to explain that irrigation influences the start of a loess landslide. For the conditions of creep motion liquefaction occurring, Wang Jiading identified the micro-tremor as a major factor [15]. Due to the role of under erosion of Loess Plateau Gully, based on the qualitative analysis of the loess landslide mechanism and field investigations, Lei Xiangyi [7], Fan Limin [18]. and Shejiao., *et al.* [19] found that the primary cause of loess landslides is the reduction of the shearing strength of loess by underground water. Xiaoyan., *et al*. [20] concluded that a rise in the hysteresis aquifer water level caused upper slope damage when irrigation water seeped into the slope, triggering loess shear and excess pore water pressure that led to the formation of a sliding surface that liquefied into a high speed flowslide. However, Ping., *et al.* [2] reported that water moves as unsaturated seepage or water vapor in unsaturated loess. When water moves the ancient soil layer with poor water permeability, water will be enriched, and moisture will be increased.

The above findings describe the relationships between water, gravity erosion, and the loess flowslide. These theories include complex processes, such as the influence of gully erosion on slope stability, the coupling of water and gravitational erosion, and the combination of multiple factors to contribute to a loess flowslide.

There are three important questions that remain to be fully addresses: 1. What a role does water erosion play in this landslide and how does it affect the sliding mechanism; 2. How are the effects of water and gravitational erosion coupled and what is the influence of this coupling on a loess flowslide; 3. What is the deformation mechanism of the contact surface between the loess and ancient soil (weakly permeable layer). Since there are still many details of the loess structural description and quantitative expression yet to be solved, additional study is required to understand effects on loess flow slides.

## The corrosion resistance of loess landslide accumulation and the distance sliding mechanism of loess flow slides

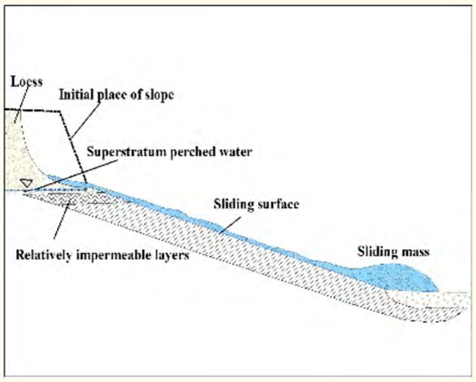
Loess with natural moisture usually presents as a solid or hard plastic state because the loess possesses some structure strength and low to middle compressibility. When loess is soaked in water, there is an obvious decrease of strength and sinking can occur in the loess. There are several models of the loess soaking deformation. Sassa [14] proposed a mechanism of particle fragmentation called "sliding surface liquefaction". It is found that the coarse particles will be crushed in the sliding and the volume is reduced, which leads to the rapid increase of pore water pressure under the condition of no drainage, and the sliding surface liquefaction. After many ring shear tests, Fawu Wang [21,22] hypothesized that slip band fragment breaking is not only beneficial to increase pore water pressure, but also to decreases osmosis. This double effect promotes the sliding surface liquefaction. After a comparison between slip soil and non-slipped soil in the Southern Tableland (Nanyuan) of Jingyang County, Shaanxi Province, Tonglu Li [23] reported that loess becomes dense from an originally loose structure with smaller porosity. The cause of the increase in pore water pressure rise is because the originally loose structure of loess has significant reductive space, rather than the particle breakage of loess [1]. These models do not include factors such as water effects to break loess structure during water erosion, and do not explain the mechanisms that contribute to loess - flow slides.

Because loess has pore structure and particles, it is a kind of soil that can easily undergo liquefaction. Studies of liquefaction of loess are needed. Liquefaction is a vitally important component of the slip mechanism but is difficult to study. Terzaghi., *et al.* [12] and Sassa [14] proposed models of slip liquefaction in which the vibration force of the sliding body caused liquefaction. Hatchinson [13] proposed a flowslide mechanism that emphasizes that the soil of the side slope must be an originally loose structure. Fangwu Wang [21] determined that the breaking of particles can generate excess pore water pressure and delay excess pore water decline effects, critical factors for a high-speed landslide. Xianli Xing [24] divided loess flowslide generation into five phases of saturated zone generation, saturated zone deformation, slope deformation, saturated zone liquefaction, and landslide becoming a flowslide. According to field research of loess flowslide with irrigation, Tonglu Li proposed three geological conditions for this kind of landslide:

1) Long-distant high slope with deep groove cutting
2) Loose loess layer with saturated moisture content over the liquid limit on the top of the slope
3) Aquifuge that can form upper sluggish water in the lower part of the side slope or gully [20].

Figure 2a-c shows three various kinds of loess landslides acting on the groundwater level. The major differences between these three are the depth of the groundwater and the eroding position. Figure 2a shows that the glide plane of loess landslide has some angle, and the lower part of loess landslide is a mudstone-water-resisting layer. Thus, liquefaction only occurs at the inner part of the loess flowslide. Figure 2b shows that with a low level of groundwater. Figure 2c shows that with a high level of groundwater, the bottom of the landslide mass is close to the groundwater level. If groundwater level is between the levels shown in (a) and (c), sliding on the smaller slope river terrace can occur. Therefore, as figure 2b shows, pore pressure generation are relatively complicated, and the liquefaction mechanism is unclear.

Additional studies are required to explore the effects of landslide mass on the flowslide, effect of the coupling between water and gravity erosion on the sliding process and determine the contributions of the loess landslide mass and loess-terrace material mixed liquefaction mechanism.



(a) Deep underground water level

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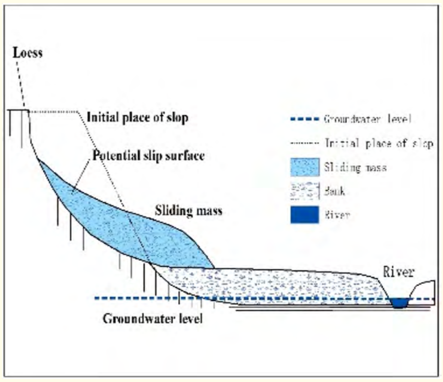
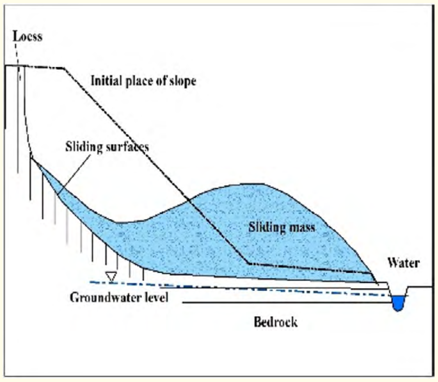


(b)Middle underground water level



(c) Higher underground water level

**Figure 2**: Schematic Diagram of The Formation of a Loess Landslide for Three Different Underground Water Levels.

## Chain evolution mechanism and forecasting method of loess flowslide disaster in coupling of water and gravity erosion

In the rainy season, a large amount of surface water and groundwater seep into the sliding body and the sliding surface. The former increases the load of the soil mass and the latter weakens the anti-sliding force of the soil and increases the lubrication of the sliding surface, which can cause landslides. There is an old proverb: “With heavy rain, the land slip becomes serious; and with a little, the land slip happens lightly” [25]. In the loess plateau gully area, Loess disasters often appear as disaster chains. For example, Ground fissures of loess will promote the development and formation of the loess landslide, after the formation of the loess landslide, because of the participation of water will evolve into loess flowslide, bringing greater harm. This disaster chain is particularly common in the loess area. The development of ground fissures along the slope of the tableland is of great significance to its formation mechanism. The coupling action of water and gravity erosion, along with the occurrence of individual landslides on the plateau, can change the geological conditions on the plateau. These changes lead to landslide development or can cause plateau edge crack development. It is not understood how the loess flowslide evolution reaches equilibrium.

The general rule of the evolution of a loess flowslide disaster is the disturbance of water and gravity leading to soil collapse, followed by ground settlement, then ground fissure, a collapse landslide, finally resulting in a loess flowslide. In a loess hilly area, a loess flowslide disaster may present different stages due to differences in topography. The key factors of the loess disaster chain are water circulation, gravity, and water - gravity coupling. However, there have been only few studies on this aspect. What are the internal relationships between geological characteristics, surface processes, water and human engineering activities, and the loess disaster chain evolution mechanism? What is the dynamic coupling between the water cycle process and the evolution of the loess disaster chain? We need to understand the loess disaster chain process under the coupling action of water and gravity erosion, and to see this information to strengthen the understanding and prediction ability of these events.

For loess flowslide prediction, current research has focused on temporal and spatial forecasting. Kuansen and Nianqin [26] in 1981 proposed a formula for landslide spatial prediction. Okuda [27] used statistical analysis of the relationship between the volume and area of landslide accumulation body to predict landslide disaster range. K Sassa [28] developed a three-dimensional landslide motion model based on the theory of fluid mechanics. The three-dimensional landslide motion simulation was applied to the loess flowslide and debris flow simulation, and it can be used to calculate about the instantaneous velocity and the accumulation range at the time of stability of landslide, which provided the basis for the prediction of the extent of damage and scope of disaster (1989). Fawu and Sassa [29] modified the value of the coefficient of friction to simulate Japanese loess landslides and mud-rock-flow. The model is simple, practical, and reliable, but requires a high-speed-ring-sheer-apparatus, to measure pore pressure. Sijing and Xiaoning [30] proposed a method that includes sliding speed and slip distance calculation. Tonglu., *et al*. [23] categorized the landslide movement of loess landslides and proposed a loess landslide prediction index and impact factor.

For time prediction, probabilistic statistics are used to forecast the occurrence of landslides according to the statistical relationship between the amount of precipitation or precipitation intensity. However, this kind of early-warning method is in early stages. To be more specific, there are three major defects with existing models:

a strong reliance on specific geological environment, large expenditure of human and material resources, and inconsistent warning standards [31,32]. Future studies could also monitor and analyze the change of seepage field induced by precipitation in slopes and the corresponding changes in slope stress field and soil strength, essential factors leading to slope instability. For example, Godt., *et al*. [33] performed suction and moisture monitoring on a potential landslide in Seattle, USA, and performed an accurate prediction of landslides. Zhang., *et al*. pointed out that the main reason for the Xiji landslide slippage was groundwater-saturated loess layer in an earthquake zone [34,35]. The main reason for the landslide in Huaxian County is the leaking of irrigation canal caused the decrease of the strength of the loess after saturation of the slope and slip failure under the action of gravity [35]. Bao., *et al.* [36] studied the influence of the soil-water characteristics on rainfall-type landslide prediction. It was concluded that the main humidification and dehumidification path could be used to predict landslide occurrence and allow the establishment of a landslide rainfall early warning reference. Jiading and Yanghe [17] conducted a survey on the Heifangtai landslide in Yongjing County, Gansu Province, and found that these landslides have the characteristics of plastic flow.

Although there have been beneficial explorations on landslides induced by precipitation from different angles, the success rate of early warning and prediction of such landslides are still not sufficient. The results from a large number of surveys indicate that previous studies overlooked three issues. First, rainfall effects on the formation of super percolation and runoff generation should be characterized on the watershed scale. Second, rainfall is passes through the large pores, vertical joints, and water holes, allowing rapid infiltration and resulting in the dual role of water and gravity erosion. Third, the infiltration process of aquifers or a relatively weak permeability layer in a short period of time allows loess saturation or near saturation and can induce loess flowslide. These three problems can be viewed as questions about the relationship between different effects of water and gravity erosion on loess flow slides. The above prevention, control techniques, and strategies are mainly based on passive prevention and control. There are no advance forecast prevention and control ideas. Therefore, how to study the mutual promotion effect of loess flowslide, how to scientifically plan projects, and to prevent the occurrence of disasters are urgently needed.

## Discussion

Existing research status had provided much insight into loess mechanisms, but the following questions still exist about loess flowslide due to coupled effects of water and gravity erosion: What is the influence of downward water erosion in the valley on slope stability? The mechanism for rapid infiltration of water-seepage diffusion-Collection-runoff-loess landslide-loess flowslide is deficient, and the characterizations of the above processes is also deficient. In the loess region, an increase in water is generally not sufficient to cause a loess landslide. In some key areas of the watershed (such as the gully bottom and the margin of loess platform), the downward erosion plays an important role to promote the loess landslide in gully. On-site monitoring or in situ experimental data is necessary to measure the hydrological conditions of water and gravity erosion leading to loess flow slides.

What is the principle of landslide accumulation body supplying the material source of the loess flowslide ? Loess landslide surface erosion resistance has a great influence on the generation of flowslide, and the effects of water and gravity erosion on loess landslides lack theoretical understanding. At present, the research has been limited to the observation and exploration of the collapse of loess. The mechanical natures of these phenomena have not been revealed, and there is no effective parameter system to characterize the mechanical behavior of the surface of the accumulation body encountering water.

What is the mutually promoting effect between loess landslide and flowslide ? Loess landslides supply the material source for flow slides and flow slides will further lead to loess landslides, but the mutual effect between these two processes requires further study. Water and gravity erosion play key driving forces in this process. At the basin scale, the water in through a complicated infiltration mechanism breaks the natural balance of water system in the loess slope and changes the hydrodynamic field. This alters the slope zone stress field to causes a loess flowslide. The research in this field is not complete, and the water and gravity erosion effects to induce loess landslides and flow slides are not understood. In particular, the effects of precipitation to induce loess flowslide need to be better characterized to allow risk assessment and early warning of potential disasters.

## Conclusions

In conclusion, though there have been quite a few achievements in loess flowslide studies, many remains unknown. To better understand the effect on loess flowslide by water and gravity coupling, the following aspects should be studied in future research.

### The effect of gully vertical erosion action on slope stability

To solve this question, research should include:

1) Dynamic mechanism of gully downward erosion action;
2) Study of differences in the loess erosion ability caused by the sediment concentration in the gully water;
3) And the influence on stress state and the stability of slope by gully basal slope erosion.

Using experiments and theoretical analysis study, quantitative characterization of the process of water's infiltration flow and diffusion should be studied for its role on loess flowslide initiation. The cooperative response mechanism of water power system and slope stress system in the process of water infiltration have been explored [2]. Based on these points, using the gully basal slope erosion for breakthrough point and the dynamics of gully vertical erosion action as starting point, a finite element model can be built on the anisotropic loess slope to include the effect of gully basal slope erosion on the stress and stability of the slope. This will quantitatively reveal the interaction between loess slope infiltration and the stress system under many different induction factors, such as precipitation, irrigation, and reservoir storage. Slope stability analysis should be based on a unit of soil body, and the loess flowslide deformation damage mechanism caused by water and gravity should be studied.

### Material source supplement principle of landslide accumulation body for the loess flowslide

There are three aspects we must understand to fully model the effects of slope deposit on soil flow, the resistance to erosion on the surface of a slope deposit, the stability of loess landslide accumulation dam, and the amplification effect of slope deposit's seepage function on soil flow patterns.

By focusing on the key area of the river basin we can model the effect of water and gravity erosion at different intensity levels and positions on loess flowslide. Artificial precipitation experiments can be performed to measure the erosion progress of water and gravity and the resistance to erosion on the surface of slope deposits. These studies should consider differences in loess terrace and hills under different hydro-geological structures, as well as the slope shape of the terrace border and the underlying surface. As a way to estimate the stability of a loess-filled dam, a basin surface water concentration model was used. That model can be used to observe tension fissure and the water accumulation activity at the bottom of sinkhole, to determine the variation of moisture content and substrate suction for different aeration zones during precipitation, to build a model of moisture movement that includes infiltration and diffusion flow at the slope area, and to quantitatively describe amplification effects of the seepage function slope deposits on soil flow provenance.

### Mutual promotion effect between loess landslide and flowslide

There are several aspects that contribute to the mutual promotion effect of loess landslides and flow slides, including the erosion action of initial and secondary landslides, the mutual promotion and disaster chain evolution mechanism for a loess flowslide, and the evolution mechanism of the loess plateau under effects of gravity and water erosion.

Given the coupling effect between water and gravity erosion, it is important to determine the changing consequences for the stability of loess regions and the potential for a flowslide. At the basin scale, it is necessary to study the mutual promotion effect between loess landslides and flow slides, based on data from unsaturated soil mechanic experiments and extensive monitoring. Testing of loess structure and composition is required to characterize the patterns soil and water, the hydraulic conductivity function, and attraction stress function to describe the erosion action of initial and secondary landslide formation. Traditional testing is required, including studies of loess disintegration, settlement, and moistening intensity to solve the boundary condition problem to study the mutual promotion effect and disaster chain effect for loess landslides and flow slides. Additionally, the influence of the process of loess deformation damage on effective stress must be characterized, and a normalized water sensitivity parameter and index system must be developed for loess systems that includes attractive stress and incorporates boundary conditions.

For loess flow slides caused by precipitation, evaluation of risk should be based on field investigation and the evaluation and zoning of susceptibility.

The monitoring of typical slope water content as well as slope stability finite element analysis allows the determination of the different precipitation characteristics corresponding to the specific slope danger threshold. Exploration of the natural balance of water systems in loess regions should be performed for loess flowslide risk evaluation and zoning based on the coupled action of water and gravity erosion on the watershed scale. Further analysis on the mechanism of changing landscapes of the loess plateau region due to effects of gravity and water erosion will enable improved risk prediction methods.

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