Research Status of Early Warning of Loess Landslides Based on Water-suction Stress-local Stability Factor

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Abstract: Loess is a special soil with strong water sensitivity. In recent years, the frequency of water-induced loess landslides has been increasing. It has caused great losses to people's lives and property. However, there is no mature early warning and prediction model of loess landslides based on water- suction stress-local stability factor now. Based on the research status of early warning of loess landslide based on water-suction stress-local stability factor at home and abroad, the authors analyzed the basic characteristics and instability mechanism of loess landslides induced by different factors. And the authors initially put forward the establishment of early warning model of loess landslide under different inducement conditions. During it, the authors analyzed the water content of loess, matric suction, suction stress, progressive failure process and local stability factor, and the research status of early warning and physical early warning models of loess landslide based on water-suction stress-local stability factor are discussed. Finally, the authors advanced a refined early warning model of loess landslide based on progressive failure principle and finite element method coupled with water-suction stress-local stability factor is proposed, which takes water as the main line, as well as the research contents and research schemes for realizing the model.

***Keywords*:** water, suction-stress, local stability factor, loess landslide, early warning

1. Introduction

Loess is a special soil with fragile structure and strong water sensitivity, widely distributed in northwest China. Loess landslides have become a typical geological disaster in the loess area due to their widespread, frequent, complex and catastrophic nature (Wang Nianqin, 2004). In recent years, loess landslide disasters caused by water as the main inducement have shown a high incidence. Loess has the characteristic of greatly reducing its strength when it encounters water. Water infiltration leads to softening of the sliding zone soil, which reduces the suction of the matrix in the soil, reduces the shear strength, and reduces the local stability factor, which leads to the progressive failure of the loess landslide, until the overall instability of the loess landslide (Peng Jianbing et al., 2014; Zhang; Mao et al., 2016). Regarding the water sensitivity, suction-stress, matrix suction, local factor of safety, progressive failure and early warning and forecasting methods of loess landslides, predecessors have carried out a A series of basic research work (Yao Hailin, 2005; Xu Liqun et al., 2008; Godt et al., 2009; Zhang Maosheng et al., 2011; Lu et al., 2012; Xing Xianli et al., 2015). However, the induced mechanism of water-suction stress on loess landslides is extremely complex, and further research is needed. Therefore, it has become an important research direction to establish a corresponding early warning model of loess landslides based on water-absorption stress-local stability factor, and to carry out early warning and forecasting of loess landslides. It is of great significance to analyze the research status of this type of landslides for the future targeted fine warning and prevention of loess landslides.

2. Types of water-induced loess landslides

Water is the most positive factor to induce loess landslides. According to incomplete statistics, 80% to 90% of the instability of loess landslides is related to the action of water (Mu Huandong, 2016). Loess landslides caused by water as the main inducement can be roughly divided into four types: precipitation, freezing and thawing, irrigation and reservoir water storage.

A lot of research work has been done on the loess landslide induced by rainfall (Wu Weijiang et al., 2006; Zhang Maoxing et al., 2009; Tu et al., 2009; Yin Zhiqiang et al., 2016; Zhang Shuxuan et al., 2017). The formation mechanism of loess landslides induced by precipitation can be divided into heavy rain type and rain type according to the characteristics of precipitation triggering landslides, and can be divided into groundwater level rising type, dominant channel-local groundwater type and increasing type according to the groundwater action mode. Rainfall flows into the ground through concentrated channels, causing the groundwater level to rise locally or the formation of stagnant water in the upper layer to cause landslides.

The instability modes of loess landslides caused by freezing and thawing can be divided into transfer type and rotation type. During the freezing period, the shear strength of the frozen layer of the slope body is about an order of magnitude larger than that of the unfrozen soil, and the permeability factor is about an order of magnitude smaller (Peng Liyun et al., 2010), which will block the groundwater drainage channel. The groundwater migrates to the middle and lower part of the slope, and the water level rises continuously. The saturation of the soil in the lower part of the slope produces a large hydrostatic pressure, which causes the phenomenon of static liquefaction, which reduces the strength of the slope soil, that is, the freezing and stagnant water effect and the melting strength decrease. Freeze-thaw cycles significantly reduce the strength of loess, and seasonal freeze-thaw effects lead to constant changes in groundwater static and hydrodynamic pressure with time, which directly affects the stress state and slope stability in the slope (Wang Nianqin and Yao Yong, 2008; Shao Hai et al. , 2018; Wang Yu et al., 2019). Among the 380 recorded loess landslides in the Yili Valley, Xinjiang, 40% occurred during the freeze-thaw period (Zhu Sainan et al., 2018).

Irrigation changes the primary hydrogeological conditions of the slope body and causes the groundwater level to rise. The soil gradually changes from an unsaturated state to a saturated state, which reduces the matrix suction in the soil and reduces the shear strength, which leads to the occurrence of loess landslides (Xu L, 2011; Zhu Lifeng, 2013; Qi Xing, 2018; Ma et al. al., 2019; Liang Yan et al., 2019). Irrigation-induced loess landslides are most typical in Heifangtai, Gansu and Jingyang, Shaanxi. Guo Chen et al. (2019) studied the disaster patterns of low-level squeezing, high-level accumulation and high-level slide-out loess landslides caused by water diversion irrigation.

Landslides caused by reservoir water storage are mainly caused by water storage changing the groundwater conditions on the slopes of the reservoir area. When the water level rises, the effective stress of the soil is reduced and its anti-sliding ability is reduced; when the water level falls, the loess has a high hydraulic gradient due to its low permeability. At the same time, the scouring and erosion of the reservoir bank changes the stress state of the slope and reduces the stability (Lei Xiangyi, 2001; Zhang Maosheng, 2011). Xiao Shirong et al. (2013) studied the reservoir water response characteristics of clay loess landslides.

Based on the summary of the above four types of water-induced loess landslide systems, the author will analyze the loess soil moisture content, water content-suction stress-local stability factor coupling relationship, and the research status of loess landslide warning and physical early warning model based on water-suction stress-local stability factor. The purpose is to provide reference for disaster prevention and mitigation of loess landslides.

3. Research status of loess landslide early warning based on water-suction stress-local stability factor

3.1 Soil water content

Because loess is a special soil with fragile structure and strong water sensitivity, this characteristic makes water have a great influence on the mechanical properties of loess. The change of water content directly affects the cohesion and internal friction angle of the soil, which in turn affects the shear strength of the soil. Therefore, studying the influence of water content of loess on its mechanical properties has become one of the focuses of loess landslide warning research.

Rainwater infiltration into the slope body is a saturated-unsaturated infiltration process. In the process of rainfall infiltration, the water content distribution on the vertical section of the slope from the surface layer is mainly divided into four areas: the saturation zone, the transition zone, the conduction zone and the wet zone. The saturated zone has the highest moisture content but is thinner. The water content of the transition zone below changes greatly. The distribution of moisture content in the conduction zone below is relatively uniform. The lowermost part is the wet zone, and the humidity gradient of the wet zone goes further and further down to the wetting front. As the rainfall continued, the scope of the influence of rainwater infiltration became larger and larger, the wetting zone and the wetting front continued to move down, and the moisture content distribution curve gradually became flat. Francesco et al. (2012) established an early warning model of critical cumulative rainfall and soil pre-water content, and studied the relationship between soil pre-water content and critical cumulative precipitation of landslides. Bujang et al. (2006), Oka et al. (2011) and Huang et al. (2012) studied the effects of changes in water content in unsaturated soil and differences in infiltration processes on landslide instability under precipitation infiltration. Muntohar et al. (2010) established a landslide stability model under rainfall infiltration to study the effect of rainfall on the instability of shallow landslides. Many scholars have carried out research on the influence of precipitation infiltration on landslide stability through field experiments. Zhang et al. (2000) obtained the variation characteristics of soil infiltration rate with precipitation process through field experiments, and established a corresponding infiltration model. Gvirtzman et al. (2008) studied the permeability characteristics of unsaturated loess through permeability test and analyzed the main factors affecting the permeability. Aurelian et al. (2008) studied the erosion rate of soil at different depths during the precipitation process, and established an equation for the variation of soil infiltration depth with continuous precipitation.

3.2 Coupling relationship of water content-suction stress-local stability factor

As an independent stress state variable, matrix suction is a very important concept in unsaturated soil mechanics, but its physical significance is rarely reported. The causes of matrix suction are related to the wettability of the liquid-solid surface and the surface tension of water. There is a meniscus at the gas-liquid interface and the fluid pressure on both sides is discontinuous. The pressure of the water below the meniscus in the capillary is lower than the atmospheric pressure, and this pressure difference is called the capillary pressure. In soil science, the negative value of capillary pressure is called matrix suction (Yao Hailin, 2005). Matrix suction is the difference between air pressure and pore water pressure. The magnitude of the matrix suction is affected by the size of the soil pore size. Matrix suction has a significant impact on the strength and deformation characteristics of unsaturated loess. The greater the suction, the higher the strength (Guo Nan et al., 2017). The soil-water characteristic curve is the relationship between matrix suction and volumetric water content. Soil-water characteristic curve (SWCC) is the foundation and bridge for studying the hydraulic properties of unsaturated soil. The mechanical behavior and hydraulic characteristics of unsaturated soil are closely related to the soil-water characteristic curve (Lu et al., 2004). White et al. (1970) and Yuan Zhihui et al. (2015) concluded that the typical unsaturated loess soil-water characteristic curve presents four distinct stages. The influencing factors of soil-water characteristic curve are soil structure, soil mineral composition, temperature and soil moisture history.

Loess is an unsaturated soil. Bishop's univariate theory and Fredlund's bivariate theory are currently the most representative strength theories for unsaturated soils (Fredlund, 1993). Both theories are derived from the Mohr-Coulomb strength theory. Both theories introduce the stress parameter of matrix suction, but the former takes it as the effective stress and the latter takes it as an independent variable. The relevant parameters in these two theories were determined using an unsaturated soil triaxial apparatus or a direct shear apparatus to control the suction of the substrate. However, this testing technology has been faced with the difficulty of long testing period and the question of the rationality of parameters. In view of this, Xing Xianli et al. (2015) used conventional triaxial CU tests with different water contents, measured the effective steady-state strength parameters, and obtained the relationship between suction stress and volumetric water content. The unsaturated strength is directly expressed by the suction stress function. The strength formula avoids the problem of determining the suction force of the matrix, and the shear strength formula based on suction stress is more convenient for engineering application.

The suction stress of unsaturated soil is a function of matrix suction or water content, and the relationship between suction stress and matrix suction or water content is called the suction stress curve (Wang Jing'e, 2012). Lu et al. (2004) proposed a shear strength formula based on suction stress, and considered all the strength of soil to be friction strength through microscopic analysis. The macroscopic cohesion of soil is shear resistance. Friction is formed between grains of unsaturated soil under the action of the normal force generated by the matrix suction; even the saturated soil also forms friction force under the action of the normal force generated by the van der Waals force. The explanation of the friction strength generated by the matrix suction is consistent with the theory of Bishop and Fredlund; the explanation of the origin of the cohesion of saturated soil is an extension of traditional soil mechanics. From this, he proposed the shear strength formula with only friction strength, and proposed the characteristic curve of suction stress to express the internal stress state of soil under unsaturated state. The use of Lu Ning's friction strength formula avoids the problem of determining the soil-water characteristic curve, but it is necessary to determine the relationship between suction stress and moisture content. The characteristic curve of suction stress can be realized by conventional triaxial test. Lu et al. (2004) defined all interparticle forces (electric double layer repulsion, capillary suction and van der Waals force, etc.) as the suction stress σ^s. They believe that the matrix suction is not a macroscopic stress variable, and needs to be multiplied by a scale conversion function factor to convert it into a macroscopic-scale stress variable representing the unit body. The suction stress is the normal stress and is a reasonable extension of the Terzaghi or Bishop effective stress. After considering the suction stress, the effective stress can be expressed as follows:

$$\sigma' = \sigma - u_a - \sigma^s \tag{1}$$

In formula (1): σ' is the effective stress; σ is the total stress; u_a is the pore gas pressure; σ^s is the suction stress.

Deng Yousheng et al. (2017) proposed a shear strength reduction method for unsaturated soils based on soil suction stress, and used the FLAC3D finite difference program for comparative analysis and verification. The shear strength reduction method of unsaturated soil based on the suction stress theory has a clearer physical meaning and is more in line with the definition of strength reduction. Zhang Maosheng et al. (2011, 2016) developed the loess water-sensitivity catastrophe mechanics theory with suction stress as the core, and established a loess water-sensitivity parameter and index system based on the suction stress theory. They proposed a progressive failure analysis theory for loess slopes based on suction stress and local stability factor, and carried out a coupled analysis of moisture content - suction stress - local stability factor. They pointed out that it is worth exploring to use the effective stress theory of suction stress to characterize the internal stress change of loess after encountering water, and to combine the existing stress-strain constitutive and known boundary conditions to jointly characterize the water sensitivity of loess.

Most of the instability failure of loess landslides is not a sudden overall failure, but a gradual failure process from partial failure to development. The progressive failure process originates from the strain softening effect of geotechnical materials. Most of the traditional slope stability calculations assume that the stability factors of all parts of the slip surface are equal. This can neither reflect the distribution law of the stability factor on the potential slip surface nor conform to the gradual failure process of the slope. The local stability factor is the stability factor of each sub-unit of the slope. Tavenas et al. (1980) and Chugh (1986) found that the local stability factors of different parts of the slip surface are not equal. Liu Lulu et al. (2016) studied the local stability factor of the slope according to the overload reserve stability factor and the strength reserve stability factor, and proposed a weighting method to calculate the overall stability factor from the local stability factor. Xu Liqun et al. (2008) defined the local stability factor of the element as the ratio of the shear strength to the shear stress on the potential sliding surface, obtained the distribution of the stability factor of slope stability, and evaluated the stability of the slope according to the distribution characteristics of the stability factor .

Take a block on the potential sliding body as the research object, and analyze the force of the block. Ti is the sliding force of the slider, and Ri is the anti-slip force provided by the sliding surface to the sliding body. The stability factor formulas for both definitions are:

$$F_i = \frac{\sum R_i}{\sum T_i} \tag{2}$$

The local stability factor F_i of the slope is defined as the ratio of the anti-sliding force to the sliding force of each micro-segment on the potential slip surface (Liu Lulu et al., 2016). From formula (2), the expression of the local stability factor can be obtained as:

$$F_i = \frac{R_i}{T_i} = \frac{\int \tau_{fi} d\Gamma}{\int \tau_{ni} d\Gamma} \tag{3}$$

In formula (3): τ_{fi} is the shear strength on the sliding surface micro-segment; τ_{ni} is the shear force on the sliding surface micro-segment; $d\Gamma$ is the length of the sliding surface micro-segment.

Wang Yu et al. (2013) discussed the temporal and spatial evolution characteristics of the gradual failure process of landslides by studying the stability factor of soil strips in the sliding zone with matrix suction under the action of rainfall. Instead of one stability factor for the entire slope, the stability factor can be calculated separately by dividing a slope into multiple regions. They used the local stability factor method to calculate the unbalanced thrust of the traction landslide.

3.3 Early warning of loess landslide based on water-suction stress-local stability factor

The literature search found that the early warning model of loess landslides under different incentives has not yet been established. The establishment of a loess landslide early warning model under the corresponding incentives based on the existing research foundation will become the focus of future research on loess landslide early warning and forecasting.

Many scholars have carried out monitoring and early warning research on loess landslides. For example, Tang Yaming et al. (2013) established three rainfall-induced loess slump models: slow infiltration induced type, infiltration penetration induced type and infiltration blocking induced type. The critical rainfall threshold for loess landslides in northern Shaanxi was obtained. Wang et al. (2013) used finite element method and strength reduction method to analyze the change of landslide stability during rainfall. Ling et al. (2012) studied the influence of groundwater on the stability of loess landslides and concluded that the increase of pore water pressure eventually led to the instability of landslides. Zhang et al. (2012) studied the groundwater level changes caused by reservoir water storage and its impact on the stability of loess landslides. Tu et al.

(2009) analyzed the infiltration of water in the soil and the changes of the corresponding soil moisture content and matrix suction through field experiments, and studied the loess landslide stability changes with time under the action of rainfall. Godt et al. (2009) carried out water content monitoring on a potential landslide in Seattle, USA, and predicted the landslide based on suction stress, which provided a reference for studying the monitoring and forecasting of precipitation-induced landslides from the mechanical mechanism.

At present, there are few studies on the refined early warning and forecasting methods of loess landslides based on water-suction stress-local stability factor. In view of the hidden characteristics of loess slope structural damage, rising groundwater level or water content, insignificant deformation, long-term evolution of loess landslides, and sudden disasters, it is difficult to capture the key factors for refined early warning and forecasting. At the same time, the induced mechanism of water-suction stress on loess landslide is very complicated. Therefore, it is urgent to carry out research on the refined early warning and forecasting method of loess landslides based on water-absorption stress-local stability factor, and develop landslide early warning and forecasting models and information platforms.

4. Early warning of loess landslide physical model

The physical early-warning model is mainly an early-warning model obtained by establishing a landslide geomechanical stability analysis and a coupled model of water infiltration. The physical model early warning of landslides is to establish corresponding early warning models for landslides with different characteristic parameters by quantifying the characteristic parameters of different landslides and establishing corresponding infiltration models. For loess landslides, rainfall causes changes in the water content of the loess body, which leads to the instability of the slope by changing the pore water pressure and matrix suction of the soil body. At present, the physical early warning model of loess landslides under the action of rainfall is mainly based on the strength theory of saturated soil or unsaturated soil. According to the rainfall infiltration process and soil characteristics, the infiltration hydrogeological model, the infiltration model and the infinite slope stability mechanical model are coupled. to judge the stability of landslides (Muntohar et al., 2010; Qi Xing et al., 2014). The model is established according to the characteristics of different landslides, and is suitable for single landslides.

For factors such as the physical and mechanical properties of landslide soil and seepage that affect the stability of the landslide mass, (Pradel et al., 1993; Ning et al., 2008; Muntohar et al., 2010; Zhang et al., 2018) have been carried out more research. Iverson et al. (1991, 1992) established an infiltration hydrological model by analyzing the soil infiltration process and seepage mode. Crosta (1998) analyzed three main factors affecting shallow landslides, namely rainfall, soil properties and landslide mass characteristics. Taking into account the slope topography, lithology, infiltration process and saturation conditions, the landslide was established by the revised Iverson model. early warning model. Lee et al. (2009) used the finite element method to analyze the soil infiltration process, and based on the infinite slope stability analysis, a PERISI model of the corresponding soil critical rainfall was proposed. Lee et al. (2009) established a coupled model for soil landslide early warning by combining the hydrological model of humidity index decay with rainfall infiltration and the infinite slope stability model. Muntohar et al. (2009, 2010) established the Green-Ampt infiltration model based on the Richards seepage control equation to analyze the changing process of the landslide stability factor during rainfall. Tsai et al. (2013) derived a hydrological model of the variation of infiltration rate with time and depth in the process of rainfall infiltration according to the Richards equation, and established a landslide stability model combined with slope stability analysis.

5. Future research directions

Water is the most active and critical factor to induce loess landslides. The rise of groundwater level caused by precipitation, melting water of ice and snow, frozen stagnant water, irrigation water, surface water and reservoir water storage, etc., or the increase of water content in the vadose zone, may cause loess landslides. How to dynamically and accurately obtain the groundwater activity of loess slopes with different slope types and gradients and the temporal and spatial distribution of water content in the vadose zone is the premise of realizing refined early warning and forecasting of loess landslides, and it has become a technical problem in the early warning and forecasting of loess landslides. The research technical route is to grasp the technical problem of the refined early warning and forecast method of loess landslides, take water, suction stress, local safety field and the principle of progressive damage as the starting point, and use field investigation, high-precision DEM, multi-source data collaboration, Air-sky-earth-internal three-dimensional monitoring and other technical means are used to study the refined early warning and prediction model and platform of loess landslides based on water-absorption stress-local stability factor (Figure 1).

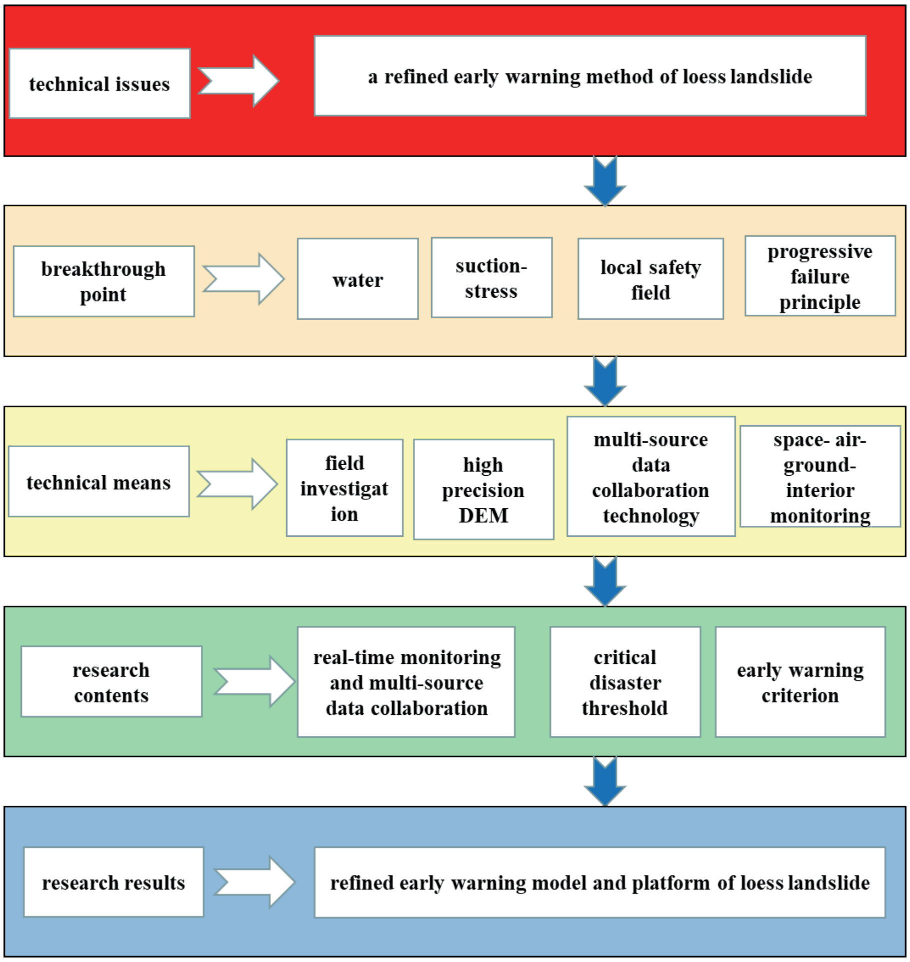

Figure 1. Research technology route

5.1 Formation of a multi-source observation system for loess landslides

Form a three-dimensional multi-source observation system based on the integration of air-space-earth-internal integration of loess landslides, study the disaster threshold, early warning criteria and forecast criteria of loess landslides, and establish real-time monitoring and multi-source data collaborative early warning and forecasting technologies for the entire process of loess landslides.

5.2 Construction of a refined early warning model for loess landslides

Study on the comprehensive response of loess slope under the action of multi-factor coupling. Establish a collaborative real-time monitoring and multi-source data collaborative early warning platform for the entire process of loess landslides based on air-sky-ground-interior. Carry out monitoring of groundwater level in loess slopes, monitoring of water content in vadose zone, and monitoring of matrix suction. The whole process is dynamically captured to obtain the structural damage process and hydrological field response of loess slopes with different slope types and slopes. Reveal the interaction mechanism between different geological structures and the water cycle under hydraulic erosion. On the basis of the research on the hydraulic coupling disaster mechanism and prediction model of loess slopes, a refined early warning model for loess landslides based on the principle of progressive failure and the finite element method coupled with water-absorption stress-local stability factor is established.

5.3 Development of a refined early warning platform for loess landslides

According to the principle of progressive failure and finite element method, the slope instability probability corresponding to the stochastic hydrological process is predicted. Utilize geological prototype analysis, indoor and outdoor testing, computer programming, database and GIS technology to design monitoring network and integrate monitoring data. Following the idea of "geological prototype investigation → early warning theoretical model optimization → monitoring information spatiotemporal data management → mathematical model generation, early warning system design → establishment of an indoor simulation test system", a loess coupled with water-absorption stress-local stability factor oriented to the slope was established. Landslide refined early warning platform. Relying on the field scientific observation base and demonstration base of typical loess landslides, improve the monitoring content, dynamically and accurately obtain the change data of groundwater level and water content in the vadose zone of loess slopes with different slope types and slopes under the conditions of different precipitation and different irrigation amounts, so as to realize Refined early warning of loess landslides with water as the main line.

6. Conclusion

Based on the literature review and practical work of loess landslide warning based on water-suction stress-local stability factor at home and abroad, this study summarizes the domestic and foreign loess landslide warning and physical warning models based on water-suction stress-local stability factor. The current research status, the existing problems and future research directions are pointed out, and the main conclusions are as follows.

(1) The basic characteristics and instability mechanism of loess landslides with different incentives are summarized. The research status of loess landslide early warning and physical early warning model based on water-suction stress-local stability factor is reviewed from the aspects of soil water content, water content-suction stress-local stability factor and so on.

(2) According to the analysis, the research on the early warning model of loess landslide based on water-suction stress-local stability factor is currently in the initial stage, and it is necessary to strengthen the research on the early-warning model of loess landslide based on water-suction stress-local stability factor under different incentive conditions.

(3) An early warning research method for loess landslides based on the principle of progressive failure and the coupling of water-absorption stress-local stability factor based on the principle of gradual failure and finite element method is initially proposed with water as the main line.

(4) A refined early warning model and early warning platform framework for loess landslides based on the coupling of water, suction stress and local stability factor are initially constructed.

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