

Research Article

The Promotion Mechanism of Frozen Stagnant Water on the Sliding in the Loess Landslide Zone of Heifangtai

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Freeze-thaw cycles can significantly change the hydrologic and thermal state of slopes in cold regions and affect their stability. Landslides occur continuously in the slip area of seasonally frozen soil area during the freezing period. The freeze-thaw action and the difference in the characteristics of the underlying surface of the slope are important factors inducing landslides. Taking Heifangtai slope in Gansu Province as an example, the freezing-thawing characteristics of the slope surfaces under different underlying surface conditions were analyzed by field monitoring. A thermohydromechanical coupling model was established to reconstruct the frozen stagnant water process of the Heifangtai landslide zone, and the impact of freeze-thaw action on the loess landslide zone was studied. The results show that differences in the underlying surface led to different freezing-thawing characteristics between the unsaturated area and the groundwater overflow zone. During the freezing period, the soil freezing depth was greater, and the freezing duration was longer in the unsaturated area. The frozen stagnant water effect of the Heifangtai loess landslide zone is obvious. The maximum difference in the groundwater level between February and August could reach nearly 1 m. Meanwhile, the frozen stagnant water process of the Heifangtai landslide zone has a slip-promoting action on the slope. The factor of safety declined during the freezing period and increased during the thawing period. It reached a minimum of 1.42 in February.

1. Introduction

Loess is distributed in 12 provinces in China, accounting for approximately 6.6% of the total land area of China [1]. Among them, Gansu and Shanxi, located in the middle reaches of the Yellow River, have the greatest proportion of loess [2, 3]. Owing to the special structure and water sensitivity of loess, the ecological environment of the Loess Plateau is fragile, and soil erosion is serious, resulting in frequent occurrence of geological disasters, especially landslides. According to statistics, the number of landslides that occur on the Loess Plateau accounts for approximately 1/3 of the total number of landslides every year [4]. A large number of loess landslides result in the destruction of arable land and the inundation of villages. With the advancement of the Belt and Road policy, the increase of engineering activities will further induce loess geological disasters. Landslides have become a major risk of human life and property safety in loess areas.

Loess landslides have been induced by long-term agricultural irrigation in the Heifangtai area. By analyzing the monthly number of landslides in this area, it was found that during the period in which the slope became frozen, although the top of the terrace had less irrigation, the number of landslides was higher. In February and March, landslide events occurred successively on the sliding surface of the slope [5], especially in areas with lush vegetation. The freezing effect and the difference in the underlying surface caused a change in the freezing-thawing characteristics of the slope surface, which promoted secondary slippage of the landslide zone. This phenomenon has attracted the attention of researchers.

There are various mechanisms that explain loess landslides induced by the freezing effect. Among them, the effect of frozen stagnant water is the most widely accepted; that is, the freezing of the slope overflow zone makes groundwater accumulate in the slope from the overflow zone, resulting in the increase of pore water pressure of soil and the decrease of shear strength [6]. The argument that seasonal freeze-thaw action in the northwestern region produces a frozen stagnant water effect and reduces the slope stability was first proposed in 1996 [7]. Meanwhile, some scholars have begun to discuss the influence of the frozen stagnant water effect on slopes through analysis of typical examples [8]. There are also some studies on mathematical models and numerical simulations of slope instability induced by the effect of frozen stagnant water in Heifangtai [9-11], which verified the rationality of slope instability induced by the freezing stagnant water effect. They divided the loess landslides in the freezing period into three stages: slope toe erosion, frozen stagnant water, and freeze-thaw cycle damage. Field monitoring of ground temperature and moisture in the study area showed that there was the frozen stagnant water effect in the Heifangtai [12, 13]. These studies have enabled us to understand that the rapid increase in slope water content results in shallow loess landslides. Triaxial tests showed that the increase in pore water pressure and the decrease in shear strength of soil caused by the effect of frozen stagnant water are important factors that induce landslides during the freezing period [14]. Consequently, it can be argued that the effect of frozen stagnant water is the main reason for landslides in Heifangtai during the freezing period.

However, the mechanism of loess landslides induced by the effect of frozen stagnant water in Heifangtai is still not well understood, especially in areas with slope slip surfaces. Soil texture and water content have a significant impact on the freezing and thawing process, resulting in differences in soil water migration, which will cause erosion of slopes [15, 16]. Further, the influence of the differences in underlying surface characteristics on slope stability and the process of "frozen stagnant water" caused by freezing is still unclear. In this study, the freezing-thawing characteristics at different positions of the slope slip surface were explored through field monitoring. At the same time, a three-field coupling numerical model was established to reconstruct the frozen stagnant water process in the landslide zone, and the influence of the frozen stagnant water process on the slope stability was analyzed. This provides a scientific basis for the evaluation and prevention of loess landslides in areas of seasonally frozen soil.

2. The Field Monitoring

2.1. Geomorphological Analysis. The Heifangtai loess platform, which is situated in the convergence of the Yellow and Huangshui Rivers, is located in Yongjing County, Gansu Province, 42 km away from Lanzhou [17]. It consists of Heitai and Fangtai, as shown in Figure 1, and the platform area is 11.58 km². The highest temperature in this area was 40.7°C, the lowest temperature was -20.1°C, and the temperature difference between day and night is large. It is an area of seasonally frozen soil. The average annual rainfall in this area is about 270 mm, mainly from May to September, and the evaporation is about 1600 mm. Because the annual rainfall is much less than the annual evaporation, and in order to resettle immigrants from the construction of Liujiaxia and other reservoirs, water lifting irrigation projects have been built since then. The annual average irrigation volume can reach 6 million m³. Long-term agricultural irrigation has raised the groundwater table by more than 20 m in the area [18, 19]. Some studies have shown that the groundwater table is still rising at a rate of 0.4 m/yr [20].

The geological structure of Heifangtai is composed of four layers: aeolian loess, alluvial silty clay, pebbles, and sand mudstone, from top to bottom. The aeolian loess is mainly composed of light-yellow silt particles, with a thickness of 21–50 m, and has vertically developed macropores and strong water sensitivity. The alluvial silty clay, which underlies the aeolian loess, is approximately 0.3–2 m thick and has obvious horizontal bedding and weak water permeability. The thickness of the pebbles that underlie the alluvial silty clay ranges between 2 and 4 m; it mainly consists of granite and quartzite, and the grain size is mostly 5–10 cm. The lowest layer is sand mudstone, which is approximately 70 m thick, with obvious bedding development, and the distribution of sand mudstone is stable [21, 22].

Field investigations have found significant differences in ground coverage types and surface soil moisture content. There are reeds and other vegetations in the groundwater overflow zone (Figure 2(a)), in which the thickest vegetation coverage was more than 1 m in height. Water content of the soil in the groundwater overflow zone was nearly saturated, which was much higher than that of soil in unsaturated zone of slope (Figure 2(b)). The freezing-thawing process of soil has been found to be closely related to soil vegetation and water content [23]. Moreover, the soil surface of the groundwater overflow zone in the study area contained a large area of white salt (Figure 2(c)). The salt concentration in the unsaturated saline soil is closely related to the freezing temperature [24]. The difference in the underlying surface and the increase in salt content will inevitably lead to different freezing and thawing characteristics between the groundwater overflow zone and the unsaturated area of the slope. Therefore, the differences in freezing and thawing between the groundwater overflow zone and the unsaturated area of the slope were analyzed through field monitoring.

2.2. Site Instrumentation. In order to analyze the changes in soil temperature and freezing-thawing characteristics at different depths of soil in the unsaturated area and groundwater overflow zone, 5TM probes were set up at the depths of 10, 50, 70, 85, and 100 cm in the unsaturated area and 40, 80, 100, 115, and 130 cm in the groundwater overflow zone. The temperature measurement range of the probe was -40° C to 60° C. At the same time, the heat flux data at the depth of 10 cm in the unsaturated area and 40 cm in the groundwater overflow zone were obtained by installing soil heat flux



FIGURE 1: Location of Heifangtai.





(a) Vegetation distribution in groundwater overflow zone

(b) Water seepage in sliding surface groove



(c) Salt-affected soil in groundwater overflow zoneFIGURE 2: Geomorphology of the study area.

sensors of type HFP01. Before the field monitoring test, the 5TM and HFP01 sensors were debugged and calibrated. When calibrating the temperature and water content, the 5TM sensor is placed in an environment that can accurately measure the temperature and water content, then record whether the measured data by the sensor is consistent with the known results, and calculate the sensor error to obtain the calibration temperature and water content formulas. When processing the data, the monitored data is substituted into the calibration formula to obtain the calibrated results.

The layout of the monitoring section is shown in Figure 3, and the onsite installation of the hydrologic and thermal monitoring instruments is shown in Figure 4. The soil temperature and heat flux were collected using a CR300 data acquisition instrument, and the data acquisition frequency was 10 min. All the data were collected via remote transmission. The monitoring period was from October 16 2018 to February 29 2020.

2.3. Analysis of Freeze-Thaw Characteristics. Figures 5(a) and 5(b) show the contour maps of soil temperature in the

unsaturated area of the slope and the groundwater overflow zone, respectively. It can be seen from the figure that during the monitoring period, the soils in the study area experienced two freeze-thaw cycles. During the freezing and thawing process, the extreme values and phases of soil temperature at different depths were different, but the temperature change cycles were roughly the same. The soil temperature in the unsaturated area of the slope began to decrease in October. It began to freeze in November and reached the maximum freezing depth in January of the following year. The figure shows that the maximum freezing depth in both periods was approximately 40 cm. In early February, the soil temperature increased, and the frozen soil gradually melted. Freezing lasted for two months. The soil in the groundwater overflow zone began to freeze in November 2018, and the maximum freezing depth of the soil exceeded 20 cm in January 2019. By the end of January, the frozen soil melted, with freezing lasting for nearly 50 days. In the winter of 2019-2020, due to the higher soil temperature in the groundwater overflow zone, the soil was almost unfrozen. According to the variation of soil temperature in a year,



FIGURE 3: Layout of monitoring section.



(a) Monitoring hole of the groundwater overflow zone

FIGURE 4: Onsite installation of monitoring instruments.



FIGURE 5: Contour of soil temperature.

the period from December to February of the following year is called the freezing period, and the period from March to April is called the thawing period. The freeze-thaw pattern experienced in a year is called the annual freeze-thaw cycle. Comparing Figures 5(a) and 5(b), it can be seen that under the same atmospheric temperature environment, the soil temperature in the unsaturated area is lower than that in the groundwater overflow zone during the freezing period, the soil freezing depth is greater, and the freezing duration is longer.

To further illustrate the influence of atmospheric temperature on the freezing and thawing of soil in the groundwater overflow zone during the freezing and thawing periods, the diachronic curves of atmospheric temperature and soil temperature at 40 cm underground in the groundwater overflow zone from February 10 2019 to February 20 2019 were plotted (Figure 6). The results show that there is a significant correlation between the atmospheric and ground temperatures in the groundwater overflow zone. Changes in the ground temperature lagged slightly behind the atmospheric temperature, and the variation range of the atmospheric temperature was slightly larger than that of the soil temperature. Moreover, during the period from February to March, the shallow soil undergoes freezing and thawing with the positive and negative fluctuations of atmospheric temperature. Approximately 20 freeze-thaw cycles occur, which are known as the daily freeze-thaw cycle. Therefore, the slope in the study area is not only affected by the annual freeze-thaw cycle but also by the daily freeze-thaw cycle. The annual and daily freeze-thaw cycles cause the slope factor of safety to decline exponentially [25], which is extremely unfavorable to the stability of the loess slope.

3. Methodology

The key challenge for understanding the thermohydromechanical coupling process of slopes in seasonally frozen soil regions is the influence of slope water accumulation on the stress field when the temperature decreases, as well as the coupling process of soil heat conduction and phase change heat transfer. In order to analyze the variation laws of the moisture field, temperature field, and stress field of the slope caused by freezing and thawing, the following numerical analysis was performed.

3.1. Moisture Field Governing Equation. According to the principle of conservation of mass, the difference in water quality between the inflow and outflow of unit soil is equal to the change in water quality of unit soil. The basic equation of the two-dimensional seepage field in the model is [26]

$$\frac{\partial}{\partial x} \left(K_x \frac{\partial H}{\partial x} \right) + \frac{\partial}{\partial y} \left(K_y \frac{\partial H}{\partial y} \right) + Q = \frac{\partial \theta}{\partial t}, \quad (1)$$

where *H* is the gross head (m), K_x and K_y are permeability coefficients (variables) in the x and y directions (m/s), respectively, *Q* is the application boundary flow (m³/s), θ is the volumetric water content (m³m⁻³);,and *t* is the time (s);



FIGURE 6: Diachronic curves of atmospheric temperature and soil temperature at 40 cm underground.

The hydraulic conductivity of the soil is calculated by the V-G model [27]. When the soil freezes, the ice crystals in the soil will hinder water seepage; thus, the ice resistance coefficient I is introduced to establish the water conductivity considering the ice resistance effect [28]:

$$K = \frac{K_0}{I},\tag{2}$$

$$I = 10^{10\theta_i},\tag{3}$$

where θ_i is the volumetric ice content (m³m⁻³). Because the moisture in frozen soil is composed of liquid water and volumetric ice content, the volumetric ice content can be expressed as:

$$\theta_i = \frac{\rho_w}{\rho_i} \left(\theta - \theta_u\right),\tag{4}$$

where θ is the sum of the volumetric unfrozen water content and ice content (m³m⁻³), θ_u is the volume content of unfrozen water (m³m⁻³), and ρ_w and ρ_i are the densities of water and ice (kg/m³), respectively. When the soil is frozen, not all the liquid water becomes solid ice. There is a proportional relationship between the volume content of unfrozen water and the temperature [29].

$$\theta_{\mu} = a |T - 273.15|^{-b}, \tag{5}$$

where a and b are parameters related to soil properties.

The freezing temperature of soil is the basic index used to determine the freezing depth of the soil. The freezing temperature of soil is not a fixed value, which is affected by soil moisture content, mineral chemical composition, and so on. To study the initial freezing temperature T_0 and the phase transition zone of the soil, the freezing characteristic curves of the soil in the slope unsaturated area and the groundwater overflow zone were drawn through an indoor freezing experiment. Firstly, the soil samples were placed in the organic glass tank, and the temperature of the circulating bath was set by the temperature control system (TMS freeze-thaw cycle equipment). The temperature intervals were set as -15, -10, -3, -1, -0.5, -0.2, 0, 3, 6, and 9°C. The unfrozen water content was measured by 5TM sensor. After connecting the data acquisition instrument, the relationship between unfrozen water content and negative temperature can be obtained by computer, as shown in Figure 7. It can be seen that the initial freezing temperature of soil in the study area was not 0°C. Owing to the influence of salt content, the initial freezing temperature of the soil in the study area had a negative value.

3.2. Temperature Field Governing Equation. Heat transfer of soil temperature changes with time; thus, based on the Fourier differential equation of structural heat transfer [30], and considering the heat conduction of the soil medium and the in situ phase transformation of ice and water, the differential equation describing the temperature field of the model is expressed as follows:

$$C\frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left(\lambda \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(\lambda \frac{\partial T}{\partial y} \right) + L\rho_i \frac{\partial \theta_i}{\partial t}, \qquad (6)$$

where *C* is the heat capacity of soil (J/($m^3 \cdot K$)), λ is the thermal conductivity of soil (W/($m \cdot K$)), and *L* is the melting latent heat of ice (J/kg). The left side of the equation represents the energy change per unit volume per unit time. The right side of the equation represents the heat conduction and ice-water phase change in the *x* and *y* directions, respectively.

3.3. Strength Reduction Method. The strength reduction method is used to reduce the shear strength parameters c and φ of the soil in equal proportions by the reduction coefficient, until the slope antisliding force is equal to the sliding force and reaches the ultimate equilibrium state. At this time, the reduction coefficient is the factor of safety of the slope [31, 32]. The reduced cohesion and internal friction angle are expressed as follows:

$$c' = \frac{c}{\text{FOS}},\tag{7}$$

$$\varphi' = arc \tan\left(\frac{\tan\varphi}{\text{FOS}}\right),$$
 (8)

where FOS is the factor of safety of the slope, c and φ are the soil cohesion (kPa) and internal friction angle (°) before reduction, respectively, and c' and φ' are the reduced soil cohesion (kPa) and internal friction angle (°), respectively.

3.4. Model Establishment and Implementation. The silty clay layer of Heifangtai is impermeable; therefore, the irrigation water is almost entirely retained in the loess layer [33]. Landslides caused by irrigation and freezing mostly occur in the loess layer. In order to analyze the frozen stagnant water effect of the loess landslide zone more clearly, the numerical calculation domain of a single loess layer was



FIGURE 7: Soil freezing curve.

established. First, a two-dimensional symmetrical slope model was used to simulate the slope instability process under irrigation. The height of the loess layer was 25 m, the length of the top terrace was 75 m, and the angle of the slope was 45° . Then, the model of the first slope sliding (Figure 8(a)) was taken as the initial model of this calculation. Considering the accumulation of soil at the slope angle after the landslide, the initial calculation domain of the model is shown in Figure 8(b).

In the temperature field, the right and upper boundaries of the model were set as convective heat flux boundaries. Such temperature boundary conditions usually use the Dirichlet boundary [34]; that is, after long-term monitoring of the boundary temperature, the empirical formula of temperature change is obtained by fitting. The lower boundary was set as the inward heat flux boundary with a value of 0.06 W/m² [30], and the left boundary was a symmetrical boundary. The ice-water phase transition was also considered in the model, and the latent heat of phase transition is 334 kJ/kg. In the stress field, the upper and right boundaries are free, the lower boundary adopts horizontal and vertical constraints, the left boundary is a horizontal constraint, and the vertical displacement is free. In the moisture field, the left boundary is a symmetrical boundary with a certain height of water head. The lower boundary is an impervious layer. The upper and right boundaries are both seepage surface boundaries, and they are derived from the V-G model. In the numerical simulation, the density of loess is 1800 kg/m³, the porosity is 0.3, the Young's modulus is $1 \times$ 107 N/m², and Poisson's ratio is 0.35 [35]. The initial values of the force field, temperature field, and seepage field can be obtained by calculating the stable distribution of each physical field after 50 years under the conditions of gravity, atmospheric temperature, and groundwater level at 20 m height, respectively.

In the slope model, the change of temperature in porous media will lead to the change of soil permeability coefficient. At the same time, the change of seepage field will lead to heat exchange between porous media and water flow. In order to achieve multiphysic coupling, a commercial software



FIGURE 9: Temperature field in the slope unsaturated area.

COMSOL was introduced, and the predefined solid mechanics module, Richards module, and solid heat transfer module are used. To ensure the convergence and accuracy of the results, the relative tolerance was set to 0.001.

3.5. *Model Verification*. The initial freezing temperature of the soil in the study area is relatively low. When the soil temperature is higher than the initial freezing temperature, the soil in the groundwater overflow zone is often saturated.

Therefore, the moisture field was not verified, and only the temperature field was verified. Figures 9 and 10 show the observed and simulated results of the temperature field at the depths of 50, 70, 85, and 100 cm in the unsaturated zone and depths of 80, 100, 115, and 130 cm in the groundwater overflow zone from October 2018 to October 2019, respectively. There are errors between the simulated and observed values of soil temperature in the unsaturated area in summer, and there are errors between the simulated and



FIGURE 10: Temperature field in the groundwater overflow zone.

observed values of soil temperature in the groundwater overflow zone in winter. However, the simulation values in the other seasons were basically close to the measured values. Owing to the inaccurate values of many empirical parameters in the numerical simulation and the complex surface boundary conditions of the slope in the seasonally frozen soil area, there are some errors in the soil temperature, but its changing trends and extreme values are relatively close to the measured values. Consequently, the constructed model and numerical simulation method can be taken as reliable.

4. Simulation Results

Taking the field monitoring values in the study area as model-driven data and considering the influence of freezing on the soil permeability coefficient and the influence of water content on the shear strength parameters of the soil, a three-field coupled transient model was established. Based on the distribution of soil temperature and pressure head in the slope, the process of frozen stagnant water on the sliding surface and the landslide-inducing effect of frozen stagnant water on the slope were analyzed. This study reports the following results.

4.1. Analysis of Freezing Stagnant Water Effect. If the soil of the groundwater overflow zone freezes during the freezing period, the groundwater level will continue to rise in the slope, increasing the dynamic and static water pressure, which is extremely unfavorable to the stability of the slope. In order to verify whether there is a frozen stagnant water effect in the Heifangtai landslide zone, a three-field coupled transient model of the slope was established to compare the distribution of groundwater and temperature fields in various periods and analyze the frozen stagnant water process. The temperature field and pressure head distribution



FIGURE 11: Distribution of temperature field and moisture field.

from February to August of the second year are shown in Figure 11.

It can be seen from Figure 11 that in February, the minimum temperature of the slope surface reached -1.64°C, and the slope surface was frozen, which prevented groundwater discharge from the overflow zone and led to the accumulation of groundwater, especially at the inflexion point of the slope. Therefore, the contour of the pressure head of the slope in February was denser than that in the other periods (Figure 11(a)). Groundwater continued

to converge, resulting in an increase in the groundwater level. In April, the soil temperature increased to a positive value, and the frozen soil on the slope melted. The groundwater was gradually discharged from the overflow zone. Therefore, the pressure head contour gradually changed from dense to sparse at the toe of the slope, and the groundwater level began to drop. Until August, the maximum temperature of the slope was 29.2°C. The continuous discharge of groundwater stabilized the moisture field.



FIGURE 12: Comparison of groundwater levels in February and August.



FIGURE 13: Maximum displacement of the slope varies with the reduction coefficient.

From the above analysis, it is clear that there is a frozen stagnant water effect in the Heifangtai landslide zone. To better analyze the impact of the frozen stagnant water effect on the groundwater level, the groundwater level data for February and August of the second year were extracted from the numerical simulation results for comparison, as shown in Figure 12. When the slope freezes during the freezing period, the elevation of the groundwater level in the slope is mainly seen at the inflexion point of the slope. The maximum difference in the groundwater level between February and August can reach approximately 1 m. This is because the groundwater continuously accumulates from the outlet of the slope toe when the slope freezes during the freezing period, resulting in a significant increase in the groundwater table at the inflexion point of the slope.

4.2. Slope Stability Analysis Based on the Strength Reduction Method. Under thermohydromechanical coupling conditions, the strength reduction method was used to analyze the slope stability in the study area. In the process of shear

strength reduction, the slope reaches the limit equilibrium state as judged by the following three points [36]: nonconvergence of finite element calculation, mutation of characteristic point displacement, and coalescence of slip surface in the plastic zone. In this study, the mutation of the displacement curve of the slope points and the penetration of the plastic strain were used as the criteria for slope instability. The relationship between the maximum displacement of the slope in October of the first year and the reduction coefficient was obtained by using the solid mechanics module in the finite element software, as shown in Figure 13. It can be seen that at the beginning of the curve, the maximum displacement in the calculation domain increases slowly with an increase in the reduction coefficient. When the reduction coefficient increases from 1.79 to 1.80, the maximum displacement in the calculation domain increases from 32.6 mm to 127.6 mm, and the curve has an obvious inflection point, indicating that the maximum displacement in the slope will increase rapidly when the reduction coefficient exceeds 1.79. Therefore, the factor of safety was preliminarily determined to be 1.79.

To confirm the safety factor of the slope, the penetration process of the plastic zone of the slip surface should be considered. Consequently, the development diagram of the slope plastic zone is drawn for a reduction coefficient of 1.79 (Figure 14(a)). When a landslide occurred again in the landslide zone in the study area, the development of the plastic zone started from the inflexion point of the slope surface. That is, the maximum displacement of the slope sliding occurred at the accumulated soil on the slope surface until the plastic region completely penetrated from the inflexion point to the top of the platform. When the reduction coefficient was 1.8, the development of the plastic zone in the slope was more obvious (Figure 14(b)); that is, the displacement of the soil sliding zone increased. However, at this time, the development state of the plastic region of the slope no longer exists, and the slope has already been damaged. According to the slope instability criterion, the factor of safety was determined to be 1.79. In the limit equilibrium state, the sliding surface is obviously arc-shaped, and its



FIGURE 14: Development of the plastic zone in the slope.



FIGURE 15: Slope sliding surface.



FIGURE 16: Changes in factor of safety with time.

sliding surface is shown in Figure 15. The direction of the arrow in the figure represents the direction of the soil sliding.

To analyze the influence of the frozen stagnant water effect on the slope stability in the seasonally frozen loess landslide zone, the factor of safety from November of the first year to May of the second year was calculated according to the above method, and is plotted in Figure 16. It can be seen that the factor of safety showed a downward trend from October of the first year to February of the second year, and the decline was the fastest in the period from December of the first year to January of the second year. There was a reduction of 8.7%, reaching a minimum value of 1.42. The factor of safety then rebounded from February to March. At this time, the factor of safety increased to 1.51 and then began to increase more slowly in March. Overall, the factor of safety decreased during the freezing period and began to rise during the thawing period, indicating that the freezing effect reduces the factor of safety in the Heifangtai landslide zone. In addition, the effect of frozen stagnant water promoted slope sliding.

5. Discussion

Freezing-Thawing Characteristics. 5.1. Differences in Through onsite monitoring, it was found that there are significant differences in freezing and thawing characteristics between the groundwater overflow zone and the slope unsaturated area in the Heifangtai landslide zone. Compared with the soil in the groundwater overflow zone, the soil in the unsaturated area reaches lower temperatures during the freezing period, higher temperatures during the thawing period, thicker freezing depths, and a longer freezing duration. This is because the water content of the soil in the groundwater overflow zone is close to saturation, which is much higher than that of the soil in the unsaturated area of the slope. The difference in water content leads to a difference in the heat released and absorbed by the soil during the freezing and thawing processes. The water content of soil in the groundwater overflow zone is higher, and the latent heat of phase change that needs to be released during the freezing process is higher; thus, the soil temperature is higher, and the maximum freezing depth is lower. Similarly, the soil in the groundwater overflow zone absorbs more heat during the phase change during the thawing period, and the soil temperature is also lower. Moreover, there are reeds and other vegetations in the groundwater overflow zone. Because of the dense root layer and organic matter of the vegetation, the soil energy transfer is changed, which affects the thermal condition of the soil near the groundwater level. The underlying surface vegetation reduces the impact of air temperature on soil temperature, which delays the freezing time of the active layer soil. The existence of vegetation reduces the freezing depth, but in the unsaturated area of the slope, the soil freezing depth is deeper because there is no vegetation cover. Loess contains a certain amount of salt, and under the action of irrigation and surface water seepage, salt migrates to the groundwater overflow zone with the groundwater. When water evaporates, salt is precipitated in a large area of the groundwater overflow zone. Studies have shown that the freezing temperature of the soil decreases with an increase in the salt content in the soil [37, 38]; therefore, the salinity in the groundwater overflow zone further reduces the freezing depth of the soil. The above three aspects make the freezing-thawing characteristics of soil in the groundwater overflow zone and unsaturated area of the slope significantly different.

5.2. Mechanism of Promoting Sliding by Frozen Stagnant Water Effect. Secondary landslides are prone to occur in the Heifangtai loess landslide zone, especially in winter and spring. Many landslides lead to a gradual reduction in the



FIGURE 17: Sliding promotion effect of frozen stagnant water on loess landslide zone.

plateau area and the formation of arc grooves inside the sliding surface. Owing to the accumulation of sliding soil, the thickness of the landslide flow area increases, which changes the shape of the slope [39]. Some scholars have referred to these as gradual retreat loess landslides [40, 41].

In the loess landslide zone of Heifangtai, the frozen stagnant water effect has had a significant impact on the stability of the slope. On the one hand, the freezing effect reduces the soil permeability coefficient and forms a stagnant water level on the slope slip surface, which increases the dynamic and hydrostatic pressure of the slope, resulting in a decrease in the factor of safety. At the same time, the difference in freezing and thawing characteristics between the groundwater overflow zone and the unsaturated area of the slope, that is, the freezing depth of the groundwater overflow zone during the freezing period is thinner, and the freezing depth of the slope unsaturated zone is thicker, resulting in continuous groundwater seepage to the bottom of the groove (groundwater overflow zone) on the slope slip surface. The soil water content on both sides of the slope slip surface is low, and the soil water content at the bottom of the groove is high. The difference in water content promotes the growth of plants in the groundwater overflow zone, which further decreases the freezing depth of the groundwater overflow zone and intensifies the seepage of groundwater to the bottom of the groove of the slip surface. The phenomenon of frozen stagnant water caused the landslide zone to gradually retreat landslides. Loess landslides have been induced by longterm agricultural irrigation in the Heifangtai area (Figure 17(a)). During the freezing period, the soil temperature decreases, forming a freezing zone on the sliding surface of the slope. Groundwater continuously accumulates in the slope to produce a frozen stagnant water effect. The differences in soil water content and vegetation cover lead to a greater soil freezing depth in the unsaturated area and a

lower freezing depth in the groundwater overflow zone (Figure 17(b)). When the temperature rises, the difference in freezing and thawing characteristics causes groundwater to seep to the bottom of the groove on the slip surface (Figure 17(c)), which induces landslides again. Frozen stagnant water has a sliding effect on the landslide zone (Figure 17(d)). The formation process is illustrated in Figure 17.

The important reason for the continuous occurrence of landslides in Heifangtai is the rise of groundwater table. Controlling the phreatic water level of the loess layer can effectively control the stability of the slope. Therefore, the utilization efficiency of crop irrigation should be given priority, and the broad irrigation in the study area should be stopped. Drip irrigation, sprinkler irrigation, and other methods can effectively control the irrigation amount. Reducing the height of groundwater level is also an important aspect of landslide prevention in Heifangtai. At present, the commonly used methods are underground drainage and surface drainage. Finally, the number of monitoring points and types should be increased, which will enable us to have a more complete understanding of the development of landslides. For example, carrying out real-time monitoring of the development of slope cracks plays a positive role in the early warning and disaster assessment of Heifangtai landslide.

6. Conclusions

 The difference in the underlying surface leads to different freezing-thawing characteristics between the unsaturated area and the groundwater overflow zone. During the freezing period, the soil freezing depth in the unsaturated area is greater, and the freezing duration is longer

- (2) The frozen stagnant water effect of the Heifangtai loess landslide zone is obvious. Freezing action will increase the height of the groundwater level, and the maximum height difference of the groundwater level between February and August reached nearly 1 m
- (3) The frozen stagnant water process of the Heifangtai landslide zone promotes landslides, and its plastic zone development starts from the bottom of the groove on the slip surface. The factor of safety decreased from October to February of the second year and gradually increased from February. The factor of safety reached a minimum value of 1.42 in February

Data Availability

The data used to support the findings of this study are available from the corresponding authors upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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