# Numerical analysis of groundwater level rise and rainfall infiltration on the stability of ancient landslide mass

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**Abstract.** Aiming at assessing the safety of an ancient landslide site, numerical stability analyses are conducted considering changes in hydraulic conditions. Through finite element simulation, two primary factors influencing slope failure, i.e., groundwater level rise and rainfall, are investigated. The results indicate that when the groundwater level surpasses the sliding zone, the stability of the ancient landslide diminishes, leading to a change in the sliding mode. The sliding mode is affected by both the water level and the dry density of soil in the sliding zone. However, landslide stability does not exhibit sensitivity to sudden heavy rainfall.

**Keywords:** Slope stability; Ancient landslide; Numerical simulation; Hydraulic environment

## 1 Introduction

The water-sensitive sliding soil, acting as the weak layer of a slope, often takes a pivotal role in slope instability [1]. During landslides, the soil in the sliding zone typically exhibits residual strength, significantly influenced by water content, direct stress, and various factors [2]. Understanding the impact of hydraulic conditions on the safety and prevention of slope failure is crucial. Specifically, the substantial effects of water content on the mechanical properties and stability of sliding zone soil should be properly considered.

Changes in the hydraulic environment can significantly affect slope stabilities, particularly in the occurrence of landslides triggered by sudden heavy rainfall and/or shifts in groundwater levels. Numerous studies have explored this phenomenon. For instance, Gu et al. proposed an extreme gradient boosting(XGBoost)-based stochastic analysis framework to estimate the rainfall-induced slope failure probability. It is found that the rain-fall intensity and rainfall pattern have significant effect on the probability of failure [3]. Zhang et al. proposed that when studying the change of slope safety factor under the dual influence of vehicle loads and rainfall, rainfall is the main cause of slope stability [4]. Liu et al. based on the principle of saturated infiltration and the Green-Ampt


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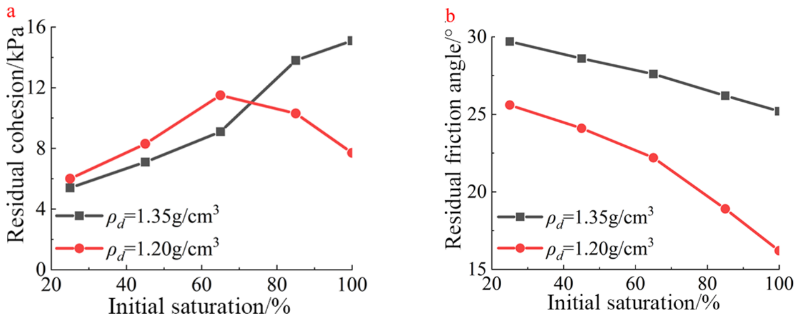
model, an unsaturated infiltration model for a soil slope surface was established for either constant moisture content, or depth-varying moisture content and the slope. Through analysis of the variation of initial moisture content in the slope, the ponding time, infiltration depth, and infiltration rate were deduced for an unsaturated soil slope subject to rainfall infiltration [5]. Zhou et al. applied numerical simulation and limit equilibrium methods to study the impact of six different rainfall conditions on the safety of waste disposal sites. They revealed the mechanism of the influence of different rainfall conditions on the stress and strain of waste disposal site slopes at different depths and spatial positions [6]. Chatra et al. used the finite difference method to explore the effects of rainfall intensity and duration on pore pressure generation, saturation degree, stability and shear strain increment. Besides, they carried out parameter sensitivity analysis on the compaction degree of slope soil[7].

This article numerically investigates the stability of an ancient landslide, considering the composition of the sliding zone soil. The impact of changes in groundwater elevation and rainfall on the safety factor of the slope is examined. Additionally, the article explores the laws governing sliding mode change and associated factors influencing the safety factor.

## 2 Influence of water table variation on landslide stability

The sliding zone is considered as the slope's soft layer. When the soft layer's thickness significantly differs from the slope's size, the limit equilibrium method can be applied to assess stability. The slope is divided into layers consisting of residual slope deposit soil, sliding body soil, sliding zone soil, sliding body soil, sliding zone soil, and medium-weathered argillaceous sandstone from top to bottom along the surface. Two sliding zones exist in the slope. The main sliding zone, situated below the two sliding surfaces, corresponds to the main sliding surface. The other sliding zone is the secondary sliding zone, linked to the secondary sliding surface. The relationship between soil strength parameters and saturation, obtained from the cyclic shear test, is illustrated in Figure 1. The cohesion of soil increases with the increase of water content within the range below the plastic limit, and the trend is opposite when the specific water content is exceeded[8-10].




a. Residual cohesion; b. Residual friction angle

**Fig. 1.** Relationship between residual strength parameters and initial saturation

Two different dry densities were considered in the study. The sliding zone with a dry density of 1.20g/cm$^3$ has a unit weight of 17.8kN/cm$^3$, and a volume water content of 0.576. The sliding zone with a dry density of 1.35g/cm$^3$ has a higher unit weight of 18.7kN/cm$^3$ and a volume water content of 0.523. Both sliding zones has a saturation permeability coefficients of 4×10-7m/s. The groundwater elevation in the landslide area ranged from 322.80~422.83m. The strength parameters of the sliding zone represent values corresponding to 100% saturation. Six groundwater elevations, i.e., 372m, 382m, 392m, 402m, 412m and 422m, are selected to for stability analysis in the subsequent calculations.

The results indicate that at low water levels, the groundwater level is approximately tangent to the main slip zone. Since the permeability coefficient of the main slip zone is small, it serves as a natural water barrier. As the water level rose to 422m, more than half of the two slip zones are below the water table and thus saturated. This leads to a deterioration in the strength of the slip zone soil, subsequently reducing the safety factor of the ancient landslide. The computed results are shown in Figures 2 and 3.

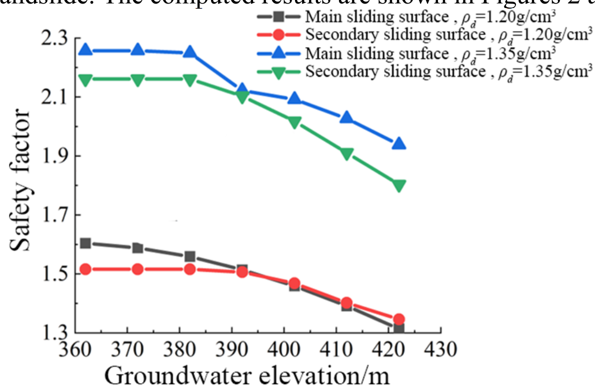



**Fig. 2.** Safety factor - groundwater elevation curve

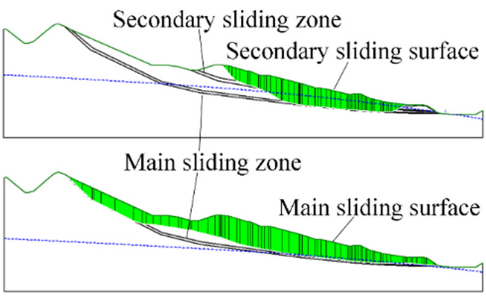



**Fig. 3.** Sliding surface modes

When the dry density of slip zone is 1.35g/cm$^3$, the safety factor exhibits a noticeable downward trend when the water level elevation exceeds 382m. In the simulation, the safety factor of the secondary sliding surface is the smallest, indicating the most dangerous situation involves local failure. However, under the influence of underground water, the sliding surface develops in the deep part of the ancient landslide, and its scope expands. In case of the secondary sliding surface, when the water level is low, the sliding surface does not intersect with the secondary sliding surface. As the water level reaches 392m, the bottom of the sliding surface has extended near the main sliding zone.

For a dry density of 1.20g/cm$^3$ in the sliding zone, the safety factor of the main sliding surface shows a declining trend. The safety factor of the secondary sliding surface remains relatively constant initially, then starts to decline. A comprehensive comparison of the safety factor curve reveals that when the local launching elevation is lower than 402m, the safety factor of the secondary sliding surface is small, and the slope exhibits shallow failure. When the water level exceeds 402m, the safety factor of the main sliding surface becomes smaller, and the slope displays an overall failure mode. Regarding the main sliding surface, it is almost entirely located in the main sliding band. This is because the slip zone soil is weaker than other soil layers, making it the weak zone of the slope. The rise of water level enhances seepage, increases the slope sliding force and decreases the safety factor. For the secondary slip surface, the primary part of the critical slip surface is initially in the secondary slip zone. When the water level elevation reaches 412m, the bottom of the sliding surface has extended into the main slip band. This occurs because the slip zone has lower strength than other soil layers. As the groundwater level continues to rise to 422m, the sliding range is reduced.

## 3 Effects of heavy rainfall on landslide stability

The rainfall intensity was set at 110mm/day. The steady-state simulation results for a groundwater elevation of 322m are introduced to minimize the influence of groundwater factors. The variation curve of the safety factor of the ancient landslide during rainfall is depicted in Figure 4. The curve exhibits a gradual downward trend, indicating insensitivity to rainfall. No change in the sliding mode occurred during the simulation. The safety of the slope based on secondary sliding surface are consistently lower than that based on the main sliding surface, indicating a shallow failure mode.

To further study the impact of rainfall on the ancient landslide, transient calculation results for the slip zone with a dry density of 1.20g/cm$^3$ are selected. The saturation distribution obtained by invoking the SEEP/W module is shown in Figure 5(a). The SIGMA/W module is used to calculate the displacement change of the ancient landslide during rainfall, as shown in Figure 5(b). The variation curve of characteristic points during the rainfall process is shown in Figure 6. After rainfall, the surface saturation of the ancient landslide increased, with a small infiltration range. Seven days into the rainfall, the displacements of the left exposed side of the slip zone, the left side of the residual slope deposit, and the foot of the slope are larger than in other areas, but the overall displacements are not substantial. At characteristic point 1, the matric suction of soil increases rapidly on the first day and then slows down. The suction of characteristic point 2 rises gently and basically returns to zero on the sixth day. The pore water pressure turns positive due to the formation of a small area of stagnant water. The displacement of characteristic points 3, 4 and 6 increases, with the growth rate gradually slowing down. The displacement of characteristic point 5 increases, but the change curve follows an "S" type. The displacement generated by the four characteristic points is between 6-14mm, which does not lead to slope failure.

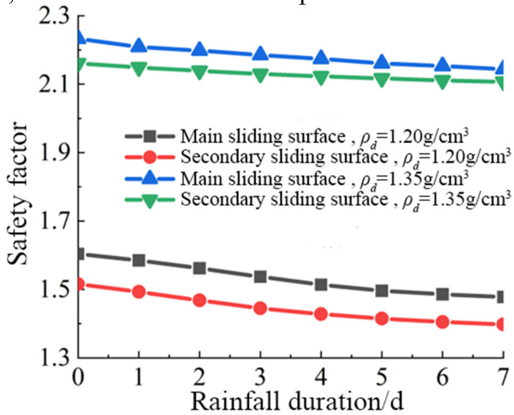



**Fig. 4.** Safety factor - rainfall duration curve

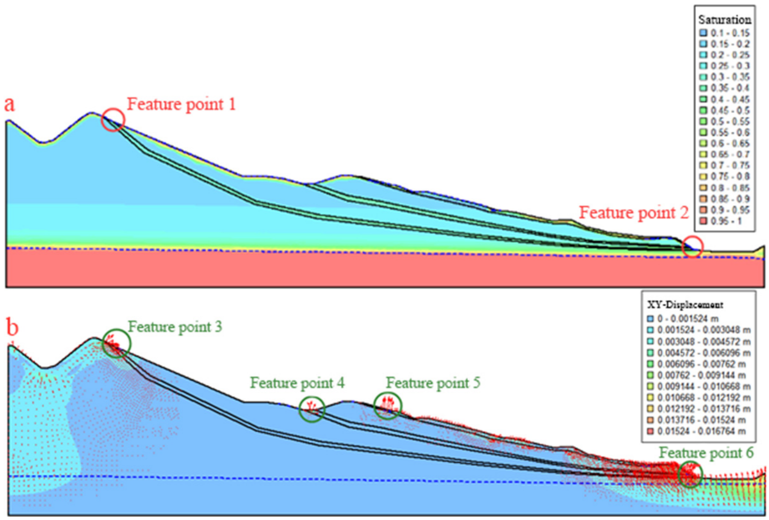
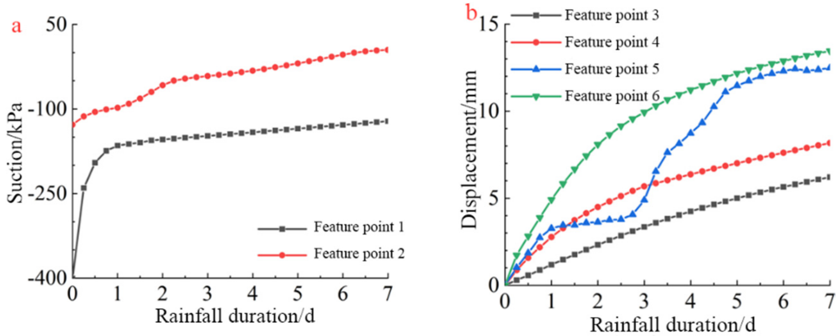



**Fig. 5.** Saturation and displacement distribution after rainfall (a. Saturation ; b. Displacement)

Combined with the calculation results of ancient landslide saturation and displacement during rainfall, it can be seen that the influence range of slope deformation and rainfall infiltration is not extensive under the continuous action of heavy rainfall at 110mm/day. Given that landslides have occurred in the past, the natural slope is relatively small, these two factors contribute to a gradual decline in the safety factor curve. Therefore, the stability of ancient landslide is not sensitive to sudden heavy rainfall.




a. Suction; b. Displacement

**Fig. 6.** Variation curve of characteristic points during rainfall ($\rho_d$=1.20g/cm$^3$)

## 4 Conclusion

In order to study the influence of hydraulic conditions on the slope of water-sensitive slip zone soil, two dry densities of 1.20g/cm$^3$ and 1.35g/cm$^3$ are used to investigate the impact of two hydraulic environmental change factors, including groundwater elevation and rainfall, on the slope safety factor. The main conclusions are as follows:

(1) In groundwater seepage, the slip zone acts as a water barrier. When the ground water level is lower than the slip zone, the slope safety factor is not affected. When it is higher than the slip zone, the stability of the ancient landslide decreases and the sliding mode changes. When the dry density of slip zone is 1.35g/cm$^3$, the slope is prone to local failure. Under the influence of groundwater, the sliding surface develops to the deep part of the ancient landslide. When the dry density of slip zone is 1.20g/cm$^3$, the most dangerous failure mode of slope will change from shallow failure mode to overall failure mode with the increase of groundwater level.

(2) Under the action of a 110mm/day rainstorm, the deformation and rainfall infiltration of the ancient landslide are not extensive. At the same time, due to the small slope, the safety factor shows a trend of insensitivity to sudden heavy rainfall. Simultaneously, the sliding surface does not change, and no new sliding mode is generated.

## Acknowledgments

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