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Research Article

The Influence of Rainfall and Evaporization Wetting-Drying Cycles on the Slope Stability

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The decay of soil strength and the change of soil infiltration characteristics caused by the dry and wet cycle effect generated by the rainfall-evaporation process are important factors that induce slope instability. How to consider the effect of soil strength decay and water-soil characteristic curve hysteresis effect on transient stability change of slope is the key to solve this problem. In this paper, transient stability analysis of slopes considering soil strength decay and water-soil characteristic curve hysteresis is carried out based on Geo-Studio. The results of the study showed that the change of transient safety factor of the slope caused by rainfall-evaporation dry and wet cycle process has an overall decreasing trend and the safety factor decreased by 43% compared to the initial state. The seepage characteristics of the rainfall-evaporation dry-wet cycle have certain regularity. The location of slope measurement points has a greater influence on the magnitude of the pore pressure change: foot of slope > middle of slope > top of slope. Also, there is a significant response hysteresis in the change of pore pressure with increasing depth at the same location. The rainfall intensity has a certain influence on the change of slope safety factor, but its influence is not obvious when the rainfall intensity exceeds a certain amount.

1. Introduction

The soil strength decay and infiltration characteristics changes caused by the wet and dry cycles lead to the destabilization damage of slope works under the rainfall conditions, and the losses incurred in the actual projects are great [1–4]. Therefore, it is necessary to analyze the influence of the dry and wet cycle process formed by rainfall and evaporation on the stability of slopes.

The wet and dry cycle affects the properties of the soil in two main ways. First, dry and wet cycles will lead to the decay of soil strength [5–9]. Second, the wet and dry cycle will lead to changes in the soil and water characteristics curve [10–13]. For example, Yang and Xiao [9], Xu et al. [8], and Li et al. [7] have studied the strength decay laws of expansive soils and clays under the action of dry and wet cycles, respectively. They concluded that the cohesive force of the soil would decrease significantly with the increase of the number of wet and dry cycles. The reduction in the angle of internal friction is relatively insignificant. The cohesion and internal friction angle will be both stable after six wet and dry cycles. Zhang et al. [12]; on the other hand, investigated the changes in soil-water characteristic curves caused by dry and wet cycles. The calculation method for predicting soil and water characteristic curves is also proposed. In the study of slope stability, Rahardjo et al. [14] investigated the relationship between rainfalls; Satyanaga and Rahardjo [15] studied the unsaturated soil mechanical properties on slope stability; Rahardjo and Satyanaga [16] monitored the slope stability by slope instrumentation. Numerical simulation of slope stability considering the effect of wet and dry cycles has also been studied by many scholars. For example, Cui et al. [17] and Li [18] investigated the effect of dry and wet cyclic action on the stability of swelling soil slopes and red clay slopes by finite element, respectively. Gao [19], Zhou et al. [20], and Li and Tang [21] further explored the effect of wet and dry cyclic action on the stability of expansive soil slopes. However, the above finite element

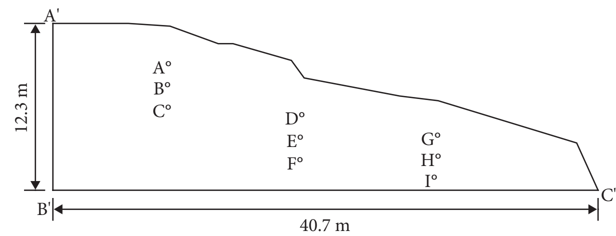

Figure 1: Computational model section.

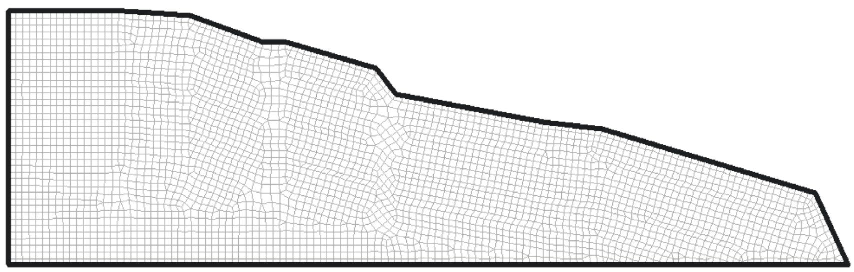

Figure 2: Model grid.

Table 1: Physical and mechanical parameters of soil.

Parameters	Dry density/(g·cm^{-3})	Poisson's ratio	Effective cohesion /(kPa)	Effective angle of friction/(°)	Permeability coefficient/(m·s^{-1})
Initial value	1.62	0.334	51	18.7	9.2×10^{-8}

Table 2: Material strength at different cycle times.

Number of cycles	0	1	2	3	4	5	6
Effective cohesion	51.0	40.1	34.9	31.5	29.2	27.4	26.0
Effective angle of internal friction	18.7	17.4	16.7	16.2	15.8	15.4	15.2

study only considered the effect of dry and wet cycles on the strength decay of the soil without considering the effect of dry and wet cycles on the infiltration characteristics of the soil. There are few reports on the effect of transient stability of slopes under the influence of dry and wet cyclic effects on soil strength and permeability characteristics in a comprehensive manner.

Therefore, in this paper, in order to comprehensively study the effect of wet and dry cycle effect on slope stability. Taking a slope project in Changsha as an example, numerical simulation analysis is carried out to consider the influence law of soil strength change and water-soil characteristic curve change on transient stability of the slope under the influence of rainfall and evaporation effect [22–24]. Subsequent experiments will be conducted using slope monitoring instruments for further research.

2. Finite Element Model Creation

2.1. Computational Models and Boundary Conditions. A typical section of a side slope project in Changsha is chosen as an example. The computational model is shown in Figure 1. The length of the side slope profile is 40.7 m. The slope height is 12.3 m.

The computational model meshing is shown in Figure 2. The mesh size is 0.1 m. The model is divided into 3341 points and 3217 units. The boundary conditions are set in the following manner. $A'B'$ and $B'C'$ are set to the impermeable boundary. The slope is set as the rainfall infiltration boundary and evaporation boundary. Also, the effect of the groundwater level is not considered. The calculation model used in this paper uses the SEEP/W and VADOSE/W modules of GEO-Studio to set the rainfall boundary and evaporation boundary parameters. After the boundary parameters are set, the slope stability coefficients of the rainfall-evaporation process can be obtained through the coupling calculation of the two modules. At the same time, different material parameters are set to simulate the changes of soil parameters for different cycle times. Thus, the dynamic change process of slope stability coefficient under the influence of dry and wet cycles is obtained.

2.2. Calculation Parameters. The strength parameters of the slope soil are determined by tests to determine the initial values. The specific parameter values are shown in Table 1. Numerous studies [9, 25, 26] have shown that the strength of the soil decays as a result of the wet and dry cycle and that the

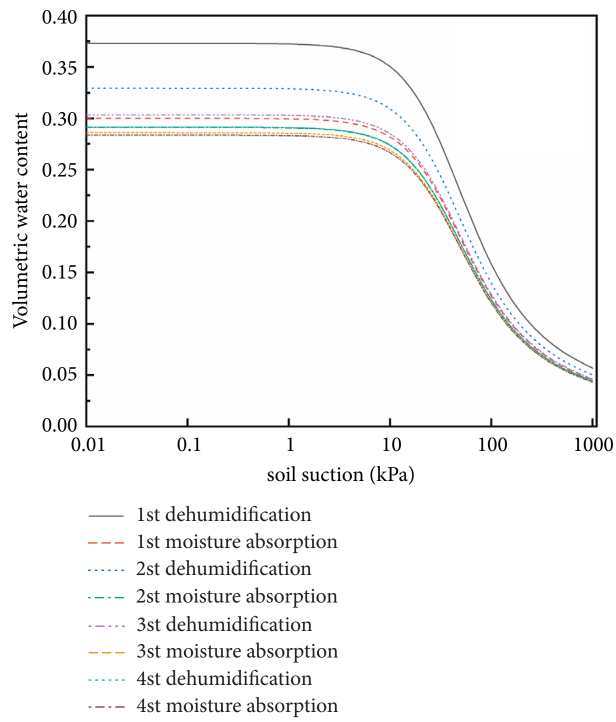

Figure 3: Water-soil characteristic curves for different number of cycles.

Table 3: Climate parameters.

Parameter name	Rainfall intensity /mm·d^{-1}	Duration of rainfall/d	Duration of Evaporation/d	Temperature/ °C	Relative humidity/%	Radiation/MJ/ d^{-1}·m^2
Rainfall	50	4	—	—	—	—
Evaporation	—	—	6	35	60	19

decay process is generally expressed as an exponential change. In this paper, the strength of the soil is fitted exponentially for different number of cycles according to the research results of Li et al. [7]. The soil strength values for different number of cycles were also calculated from the initial strengths in Table 1. The specific parameters are shown in Table 2. The unsaturated shear strength property used in this study in the analytical setup is the phi b angle.

The effect of wet and dry cycles on soil properties will have a hysteresis effect on the water-soil characteristic curve of the soil in addition to strength decay. This paper uses the results of Zhang et al.'s [12] research to predict the hysteresis changes in the soil and water characteristics curve after dry and wet cycles. The soil and water characteristic curves used for different number of cycles are shown in Figure 3. The change in the soil and water characteristics curve is predicted to stabilize after the 4th wet and dry cycle. Therefore, this paper only considers the effect of four wet and dry cycles on the soil and water characteristic curves [27–30]. Both cycles

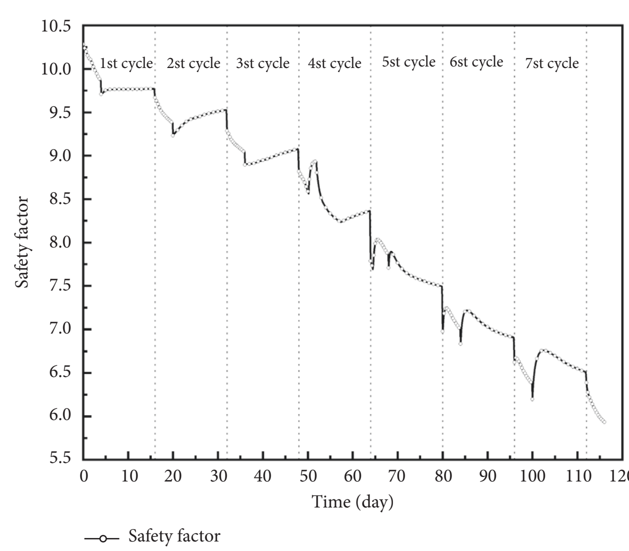

Figure 4: Slope safety coefficient change curve with time.

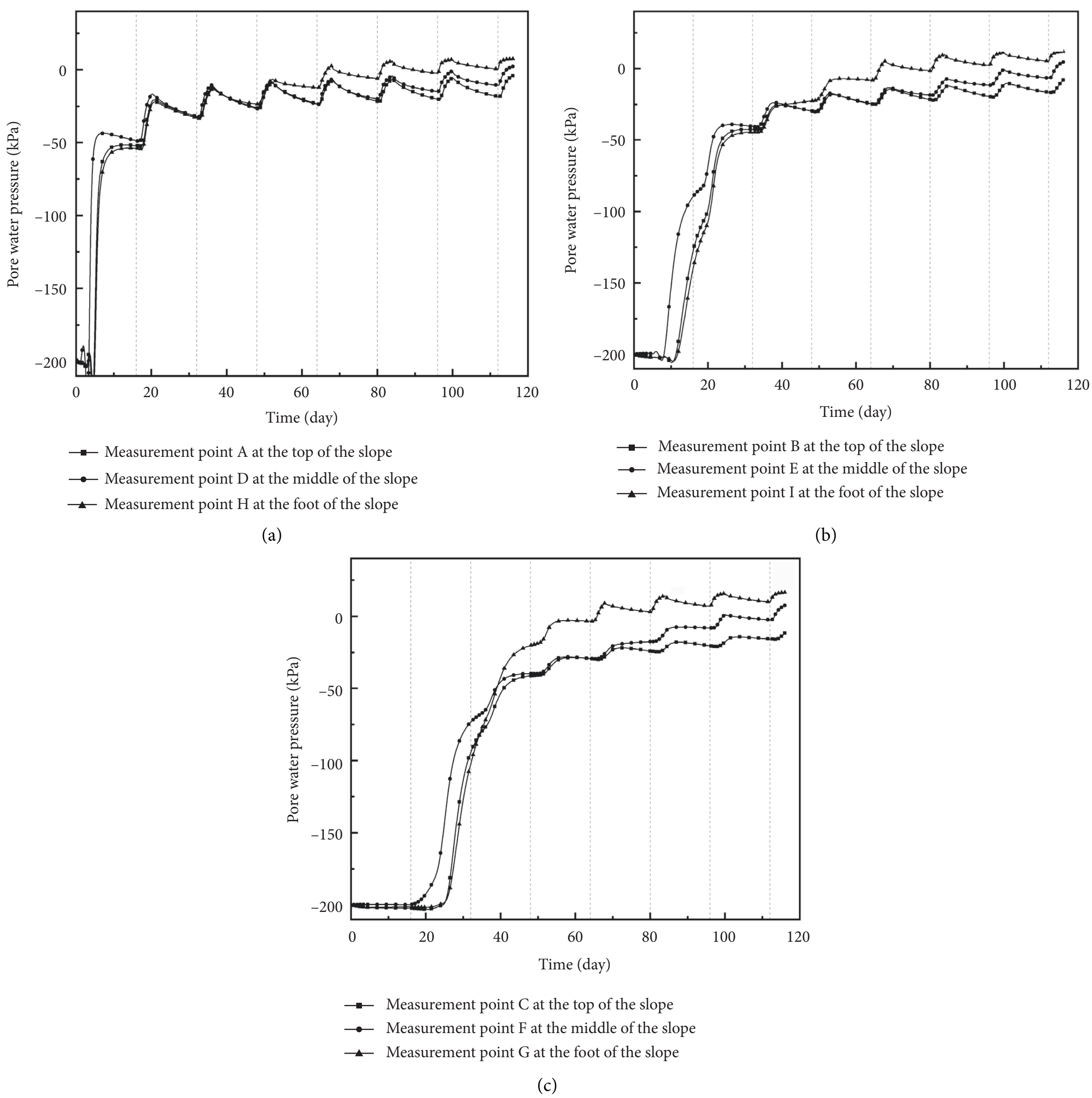

Figure 5: Variation curve of pore water pressure at different depths. (a) Pore water pressure variation curve at 3 m depth. (b) Pore water pressure variation curve at 4 m depth. (c) Pore water pressure variation curve at 6 m depth.

after the 4^{th} are replaced by the soil and water characteristic curve of the 4^{th} cycle. In this paper, the unsaturated permeability characteristics of the studied soils are described by means of water-soil characteristic curves. The relevant research results of Kristo et al. [31] are also referenced.

2.3. Analysis Settings. This paper uses the SEEP/W module of GEO-Studio coupled with the VADOSE/W module for seepage and evaporation analysis. According to meteorological data for Changsha, 4 days of rainfall and 6 days of evaporation are used as a dry and wet cycle. Specific climatic parameters are shown in Table 3. The analysis time step is set to 2 hours in one step. In order to consider the hysteresis variation of soil strength decay and soil-water characteristic curves, this paper simulates by replacing materials in layers and defining the properties of different materials. The depth of atmospheric influence is assumed to be 6 m [20] and is considered to vary exponentially with the number of wet and dry cycles.

3. Calculation Results and Analysis

3.1. Stability Analyses. The effects of different numbers of wet and dry cycles on the stability coefficients of slopes are shown in Figure 4. From Figure 4, it can be seen that the 1^{st}

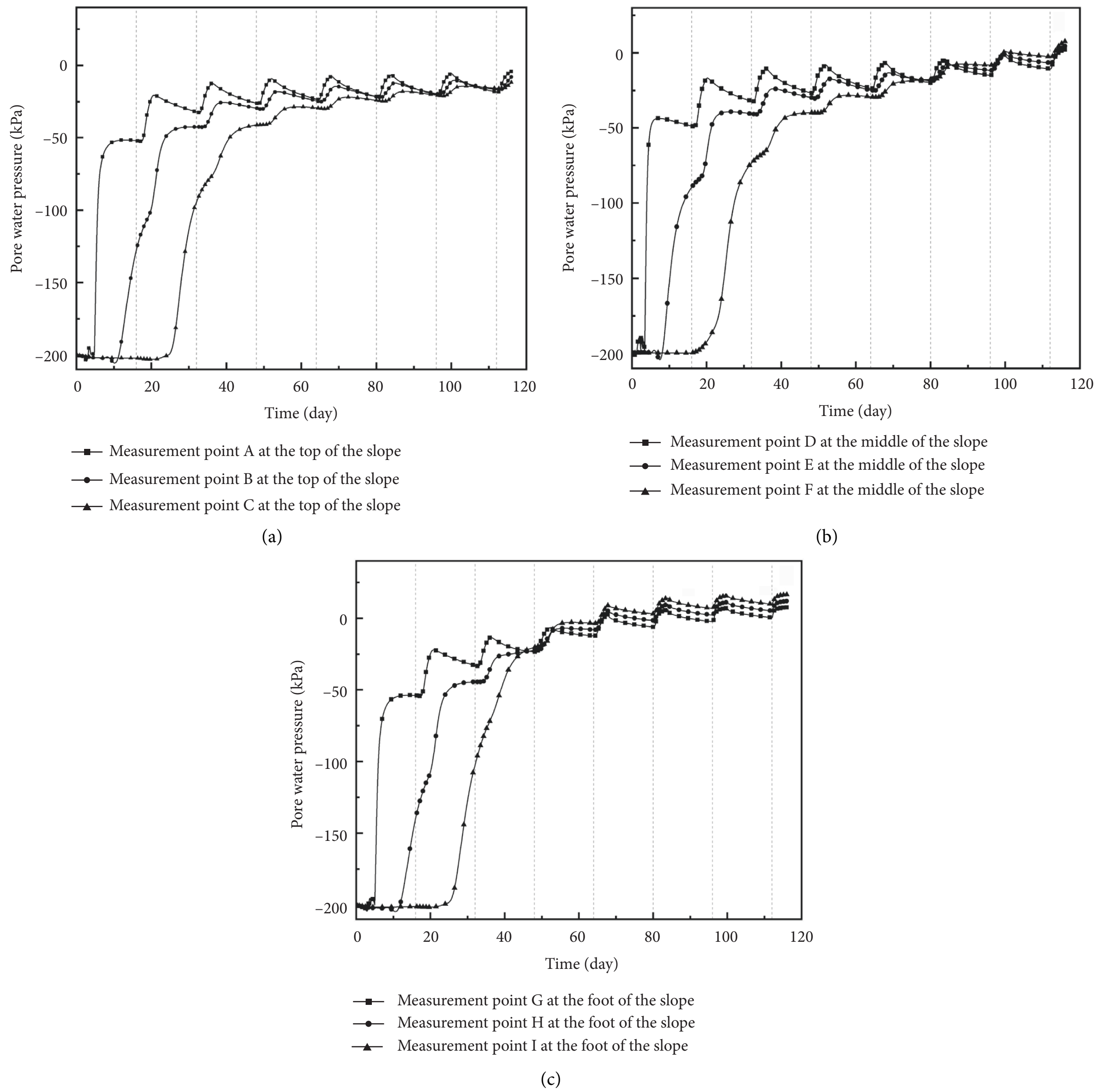

Figure 6: Variation curve of pore pressure at different positions. (a) Pore water pressure variation curve at the top of the slope. (b) Pore water pressure variation curve at the middle of the slope. (c) Pore water pressure variation curve at the foot of the slope.

cycle evaporation process has no effect on the safety factor. The 2^{nd}–4^{th} evaporation process has a clear tendency to increase its safety factor. Also, the safety factor in the evaporation phase of the 5^{th}–7^{th} cycle still shows a decreasing trend after the rebound. The reason for this result may be due to setting the initial pore pressure value of the slope to −200 kPa without considering the effect of groundwater level. Therefore, evaporation after the first rainfall infiltration is small and makes the change in the safety factor for the first evaporation phase relatively insignificant. The 2^{nd}–4^{th} cycles, on the other hand, are based on the first cycle, so the evaporation is no longer affected by the initial pore pressure. The change in pore pressure resulting from the evaporation phase increases the strength of the soil and thus the safety factor. The reason for the continuous decrease of the safety factor in the evaporation phase during the 5^{th}–7^{th} cycles after the rebound may be due to the increasing depth of rainfall infiltration as the number of cycles increases. The water content of the deep soil has a large increase from the initial state. However, the variation of water content in the evaporation phase is gradually weakened with the increase of depth. Therefore, in the evaporation phase instead, the safety factor will rebound a certain amount and then show a decreasing trend.

In general, the overall slope safety factor shows a decreasing trend with the increase in the number of wet and dry cycles. Also, relative to the initial safety factor of 10.28, the safety factor after the 7th cycle was only 5.9 with reductions of nearly 43%.

3.2. Seepage Analyses. A total of nine measurement points were set up within the slope in order to monitor the changes of seepage process during the rainfall-evaporation cycle. The locations of the measurement points are shown in Figure 1. Figure 5 shows the variation curve of pore water pressure at the same depth at different locations. It can be seen from Figure 5(a) that the variation of pore water pressure at the top, middle, and foot of the slope in the 1st to 3rd cycles is almost the same. The pore water pressure at the foot of the slope has a large deviation from the top and foot of the slope at the beginning of the 4th cycle. The position in the middle of the slope, on the other hand, is deviated from the foot of the slope in the evaporation phase of the 6th cycle. Also, on the magnitude of the change in values, the foot of the slope > the middle of the slope > the top of the slope.

It can be seen from Figure 5(b) that the variation of pore water pressure at 4 m depth is significantly different from that at 3 m depth. In the 3rd cycle, the pore water pressure at the foot of the slope starts to deviate from that in the middle and foot of the slope. It can also be seen that the pore water pressure at depth 4 m stabilize only at the end of the 2nd cycle. Also, the 3 m depth is basically stabilized at the end of the 1st cycle. However, in terms of the magnitude of pore water pressure change, it is also consistent with the foot of slope > middle of slope > top of slope.

From Figure 5(c), it can be found that the pore water pressure variation at 6 m depth is basically unchanged after the completion of the 1st cycle. It is during the 2nd cycle phase that significant changes start to occur. This indicates that there is a significant hysteresis effect of pore water pressure change in the deep soil relative to the surface soil.

It is easy to see that the pore water pressure changes in different depths of the soil layer are not the same, but the rule of foot of the slope > middle of the slope > top of the slope is the same in terms of the magnitude of change. At the same time, the hysteresis effect of depth on the pore water pressure change gradually increases with depth.

To further investigate the effect of depth on the variation of pore water pressure, the variation curves of pore water pressure at different depths at the same location are given in Figure 6. The hysteresis effect of depth on the variation of pore water pressure can be seen more clearly in Figure 6. Also, this phenomenon was present in different locations. At the same time, it can be seen from the analysis of Figure 6 that the variation of pore water pressure at different depths at the top of the slope converges basically only in the 7th cycle. The middle of the slope, on the other hand, is largely convergent in the evaporation phase of the 5th cycle. The foot of the slope is converging at the end of the 3rd evaporation. This indicates that there is a significant difference in the time for the pore pressure change to stabilize at different locations. The change at the foot of the slope will stabilize at an earlier time, followed by the mid-slope position and finally the top-of-slope position.

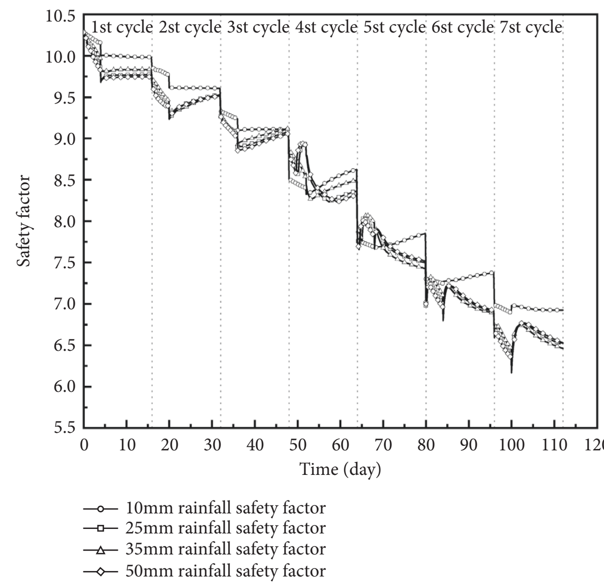

Figure 7: Variation curve of safety factor for different rainfall intensity.

3.3. Effect of Rain Intensity Variation on Stability. In order to explore the influence of rainfall intensity on slope stability coefficient, four different rainfall intensities (10 mm/d, 25 mm/d, 35 mm/d, 50 mm/d) are set for analysis in this paper. The calculation results are shown in Figure 7. According to Figure 7, it can be seen that 10 mm/d rain intensity has no significant change in the safety factor during the evaporation phase of the 1st–3rd cycles. This is mainly due to the low intensity rainfall resulting in a low impact of infiltration on the initial pore water pressure, which in turn allows the evaporation phase to be affected. Also, comparing the change of the safety factor for different intensity of rainfall shows that the overall safety factor for 10 mm/d rainfall intensity is higher than the rest of the rainfall intensity. Also, the difference in the variation of the safety factor for rainfall intensity bars above 25 mm/d is not significant. This indicates that although the effect of rainfall intensity on the change of the safety factor exists, there will be no significant difference in the change of the safety factor once the rainfall intensity exceeds a certain value. The reason for this phenomenon may be that the rainfall intensity is no longer controlled by the rainfall intensity but the infiltration capacity of the soil after exceeding a certain size, which leads to a convergence of the change in the safety factor.

4. Conclusion

In this paper, the transient stability change process of soil strength decay and water-soil characteristic curve hysteresis effect during rainfall-evaporation dry and wet cycles is considered by numerical simulation. Based on the results of the analysis the following conclusions were obtained.

(1) With the increase of the number of wet and dry cycles, the strength parameter of the slope soil will be decayed continuously. Also the water-soil

characteristic curve will have a hysteresis effect. The superposition of two factors will lead to an overall decreasing trend of slope safety factor and the safety factor decreased by nearly 43%.

(2) The seepage characteristics of rainfall-evaporation dry-wet cycle processes have obvious regularity. The location of the measurement point on the slope has a great influence on the magnitude of pore water pressure change: foot of the slope > middle of the slope > top of the slope. Also, there is a significant response hysteresis of pore pressure change with increasing depth at the same location.

(3) There is a certain influence of rain intensity on the slope stability during the wet and dry cycle. However, their effects gradually diminish and converge with the increase of rainfall intensity.

Data Availability

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

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this article.

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