Influence of Rainfall Intensity and Type on the Stability of Bank Slope

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Abstract. Rainfall is a significant factor of bank slope collapses. In this study, the effects of rainfall intensity and type on bank slope stability are investigated. By establishing non-ponding infiltration models and ponding infiltration models, the bank slope stability model considering rainfall is proposed. The results show that rainfall infiltration rapidly increases the water content of the bank soil, the safety factor of bank slopes decreases rapidly, and may even lead to the instability of bank slopes. In addition, the type of rainfall also has an important effect on slope stability, where the early occurrence of rainfall peaks affecting the slope safety factor earlier, and the later occurrence of rainfall peaks threatening the slope stability more seriously. The study highlights the importance of precautionary measures to cope with extreme rainfall in the design and management of bank slopes, including monitoring and predicting changes in bank slopes and implementing effective protective measures and drainage systems to maintain bank slope stability.

Keywords: Bank slope collapse, Stability, Rainfall, Intensity and type, Numerical modeling.

1 Introduction

Rainfall-induced slope collapses are frequent worldwide, and the number caused by extreme rainfall is increasing with climate change [1]. Cho and Lee [2] explored the destabilization mechanism of unsaturated slopes under rainfall conditions, which showed that the spatial variation of the hydraulic conductivity during rainfall has a great influence on slope the stability. Ering and Babu [3] investigated the mechanism of rainfall induced landslides considering uncertainty in soil permeability coefficient and shear strength parameters using the 2014 Malin landslide in India. Although there are studies on the mechanism of rainfall-induced slope instability, the simulations considering rainfall characteristics are still limited, and in-depth studies are needed.

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This study focuses on the effects of rainfall intensity and type on slope stability. This study proposes a non-ponding infiltration model and a ponding infiltration model for the effect of precipitation on slope stability and establishes simulation models for different rain patterns to analyze the effects of rainfall on slope seepage and stability. This study not only reveal how rainfall affects slope stability, but also provide scientific basis for predicting and preventing related natural disasters.

2 Materials and Methods

2.1 Rainfall Infiltration Modeling

The rainfall infiltration process can be divided into two stages: the rainfall intensity-controlled infiltration stage and the infiltration capacity-controlled infiltration stage, with ponding point t_p as the dividing point between the two stages. According to the size of rainfall intensity and the size of soil permeability coefficient, the effect of rainfall on the slope is divided into two types of models, non-ponding infiltration model and ponding infiltration model. The theoretical ponding point under ideal conditions are [4]:

$$t_p = \frac{(2R-K_s)S^2}{4R(R-K_s)^2}, \qquad S^2 = 2(\theta_s - \theta_0)K_s S_f \tag{1}$$

Where, t_p is the actual ponding point time (s), S is the soil moisture absorption rate (m/s), K_s is the saturated hydraulic conductivity (m/s), R is the intensity of rainfall (m/d), θ_0 is the initial soil water content, θ_s is the soil saturated water content, and S_f is the average soil water suction at the wetted front (m).

2.2 Design of Rainfall Conditions

In order to better analyze the stability of slopes under different rainfall intensities, several intensities are set up as 10 mm/d, 20 mm/d, 40 mm/d, 80 mm/d, 150 mm/d, 250 mm/d, 350 mm/d, and 400 mm/d. Different types of rainfall lead to different responses on the stability of bank slopes. Four rainfall types are selected for comparative analysis: uniform rainfall, advanced rainfall, central rainfall, and delayed rainfall [5]. The duration of rainfall is 24h and the simulation duration is 120h (5d).

2.3 Models and Boundary Conditions

For the actual picture of the bank slope in Fig.1a and the simulation geometric bank slope is simplified in Fig.1b. The quadrilateral and triangular grids are used, the grid size is 0.5m, and the grid-independent model has 8956 grid cells and 9153 nodes.

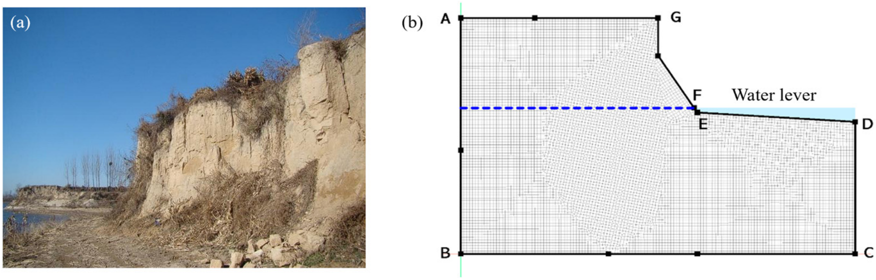

Fig. 1. (a) Photograph of the study area; (b) Geometric model of the slope.

The physico-mechanical parameters of each geotechnical body and the hydromechanical characteristic parameters of the soil required are shown in Table 1. The soil-water characteristic curves and permeability coefficient function curves of the soil are obtained by fitting the Van-Genuchten model.

According to the saturated hydraulic conductivity of the soil, the bank ponding water is determined. When the rainfall intensity is less than the saturated hydraulic conductivity of the soil (371.52 mm/d), all rainwater can be infiltrated, and the non-ponding infiltration model is used for calculation. When the rainfall intensity is larger, the bank slopes may be waterlogged. The soil moisture absorption rate and the ponding point time tp are calculated by equation (1).

Boundaries F-E-D are head boundaries to simulate reservoir levels. Impervious boundaries are set on the left (A-B), right (D-C), and lower (B-C) boundaries. At non-ponding infiltration conditions, for the first 24h of rainfall, boundaries A-G-F are set with corresponding rainfall intensity flow. At ponding infiltration conditions, before the ponding point (8787s), boundaries A-G-F are set with flow corresponding to the rainfall intensity, for the 8787s to 24h, boundaries are set with 0.01 m head to simulate ponding infiltration, and zero-flow boundaries are set for 24h to 120h.

Table 1. Bank slope soil parameters [6].

Saturated Hydraulic conductivity / m/s	Cohesion / kPa	Friction angle / °	Saturated volumetric water content	Unite weight / kN/m^3	Average particle size / m
4.3×10^{-6}	16	26.4	0.4	18.0	1.6×10^{-5}

3 Results and Discussion

In this section, seepage and stability analyses were conducted to assess the dynamics of water infiltration and moisture distribution within the slope system. The variation in soil water content at the midpoint of the top of the bank slope under different rainfall intensities is shown in Fig. 2(a). It is observed that higher rainfall intensities lead to faster increases in water content and a greater likelihood of reaching saturation. Notably, at a rainfall intensity of 400 mm/d, an abrupt change in water content at 8587 seconds is attributed to software simulation, where the surface layer is saturated, which likes the actual condition where ponding occurs before full saturation of the upper soil layer.

Fig. 2(b) depicts the changes in soil water content at the midpoint of the bank slope under various rainfall patterns. Initially, all patterns show a rapid rise in moisture due to infiltration, with the advanced rainfall type, featuring higher initial intensity, exhibiting the most significant early increase. As rainfall progresses, uniform and central patterns exhibit steady increases with minimal fluctuations, while the advanced type shows a deceleration in growth due to reduced intensity and nearing saturation. The delayed type, initially slower, and accelerates later due to higher rain intensity, resulting in a higher final stabilization value.

In the later stages, the curves of soil water content display different across types. For uniform and delayed types, the infiltration exceeds drainage, approaching saturation. Conversely, in advanced and central types, drainage surpasses infiltration, leading to a decrease in soil water content.

Overall, the temporal distribution of rainfall impacts slope infiltration significantly, with the advanced type leading to rapid but slower decreases, and the delayed type showing slower initial increases but higher final moisture content. Uniform type demonstrate moderate increases and the central type increases at first and the decreases.

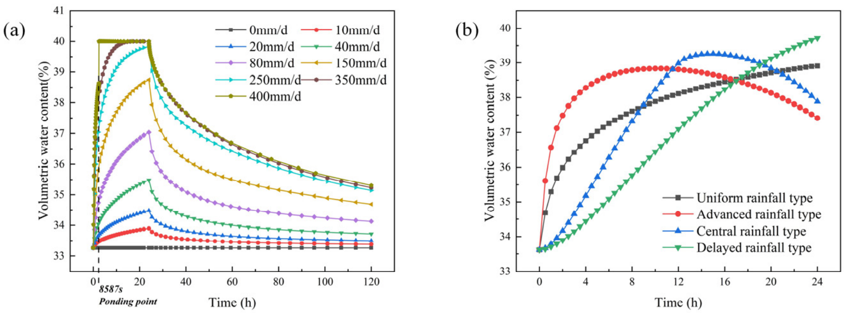

Fig. 2. Variation of water content at the top midpoint under different rainfall. (a) different intensities of uniform type rainfall; (b) different rainfall types, rain intensity 150 mm/d.

Following the seepage analysis, this section addresses the stability of the slope under varying hydrological conditions. Fig.3(a) shows the safety factor of bank slope under different rainfall intensities. It is found the safety factor of the bank slope is 1.155 at the rain beginning, indicating that the bank slope is stable. During the 24h rainfall, the safety factor of the bank slope decreases, indicating that the stability of the bank slope is gradually weakened. When the rainfall stops, and the safety factor rises slowly and gradually returns to the initial value if the bank slope does not collapse. When the intensity of rainfall is large, the safety factor decreases fast, and the corresponding recovery process is long after rainfall stops. When the rainfall intensity is 250mm/d, the safety factor of the bank slope drops to 1.05, and the probability of bank slope collapse is large. If the rainfall intensity exceeds 250 mm/d, the safety factor further decreases to 1, which means that the bank slope is collapsed.

It is found that rainfall has a significant impact on the stability of bank slope. The stability of bank slope will be seriously threatened under large rainfall intensity, and it is necessary to take corresponding protective and monitoring measures to ensure the safety and stability of the bank slope.

Fig.3(b) shows the safety factor of bank slope under different rain types. It can be found that the effects of rainfall type on the safety factor are significantly. Under the uniform rainfall type, the safety factor almost uniformly decreases. Under the advanced rainfall type, the safety factor decreases rapidly in the early of rainfall corresponding the intensity of heavy rainfall at the beginning of the rainfall, and the stability of the bank slope decreases rapidly, which indicates that the high intensity of rainfall has a significant adverse effect on the safety factor of bank slope.

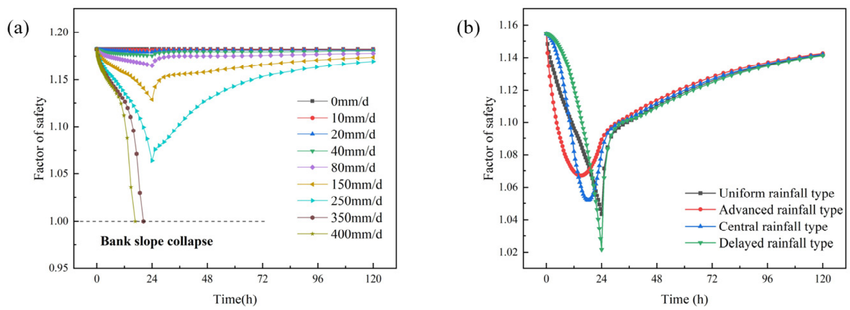

Fig. 3. Safety factor of slope under different rainfalls. (a) different intensities of uniform type rainfall; (b) different rainfall types, rain intensity 150 mm/d.

The central type of rainfall is characterized by the rainfall intensity reaching the peak in the middle period of the rainfall, and the corresponding safety factor has the fastest decreasing rate simultaneously. As the rainfall intensity decreases, the moisture of bank soil is reduced, and the change rate of safety factor becomes small, and the safety factor is decreased slowly. As the rainfall approaches end, the rainfall intensity decreases, and the reduction rate of the safety factor gradually decreases. When the rainfall intensity is small enough, the safety factor increases, and the bank slope becomes more stable. For the delayed rainfall type, as the rainfall intensity increases, the change rate of safety factor gradually increases, the safety factor decreases, and the bank slope is more unstable.

In short, as the intensity of rainfall increases, the change rate of safety factor gradually increases, the safety factor decreases, and the bank slope becomes more unstable. As rainfall intensity decreases, the change rate of safety factor of the bank slope gradually decreases, the decrease in safety factor slows down, and the instability of the bank slope increases slowly. When the rainfall intensity is less than a certain value and to stop, the safety factor is increased and recovered to its original one before the rainfall.

4 Conclusions

The effects of rainfall intensity and peak distribution on slope stability are analyzed by numerical simulation. The main conclusions are:

(1) Rainfall intensity has a significant impact on bank slope stability. Rainfall infiltration leads to a rapid increase in soil water content and decreases the bank stability. Intense rainfall may cause the safety factor to drop below 1, resulting in bank collapse.

(2) The safety factor of bank slope is directly related to the distribution of rainfall intensity. When the instantaneous rainfall intensity increases, the safety factor of the bank slope decreases rapidly. When the instantaneous rainfall intensity decreases to a certain value, the safety factor gradually increases towards the pre-rainfall safety factor.

(3) The impact of rainfall on the bank stability varies depending on rainfall type. As the rainfall peak shifts back, the impact of rainfall on the safety of bank slopes increases, making it more likely to cause bank slope collapse.

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