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Seepage and Stability of an Earth Dam under the Condition of Rainfall Infiltration

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Abstract. The effect of precipitation on the pore pressure of water in the soil and the stability of the slope of an earthen dam is investigated. The earth dam at Khac Khoan reservoir in Binh Phuoc province, Vietnam, was chosen as the case study. In doing so, the SEEP/W and SLOPE/W modules of the GEOSTUDIO software simulate the effects of rainfall on the changes of pore-water pressure of soil and the stability of the earth dam. Four distinct rainfall scenarios representing different intensities were used for the analyses to assess their impact on soil pore-water pressure and stability of the earth dam. The results show that rainfall induces notable changes in pore-water pressure and reduces slope stability, with the magnitude of these effects varying by scenario. Among the scenarios, the moderate-intensity, prolonged rainfall (Scenario 3) exerted the most significant destabilizing influence. Understanding how rainfall alters pore-water pressures and slope safety factors is crucial for evaluating stability under worst-case conditions and formulating appropriate operational and maintenance strategies.

Keywords: Slope stability, Effects of rainfall on slope stability, Numerical simulation, Prolonged rainfall, Landslide

Conflicts of interest. The authors declare that there is no conflict of interest.

Authors' contribution: *Nguyen H.P.T.* — methodology, software, writing; *Pham N.T.* — conceptualization, visualization, writing — review and editing; *Nguyen T.M.S.* — visualization, writing — review and editing; *Ngo V.L.* — visualization, writing — review and editing; *Dang V.P.* — validation, supervision, conceptualization, writing — review and editing.

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Фильтрация и устойчивость грунтовой плотины при просачивании дождевой воды

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Аннотация. Исследовано влияние осадков на поровое давление воды в грунте и устойчивость откоса грунтовой плотины. В качестве объекта исследования была выбрана грунтовая плотина водохранилища Хакхоан, расположенного в провинции Биньфыок, Вьетнам. Для моделирования влияния осадков на изменение порового давления воды в грунте и устойчивость откоса использовались модули SEEP/W и SLOPE/W программного обеспечения GEOSTUDIO. Анализ проводился на основе четырех различных сценариев выпадения осадков, представляющих собой различные уровни интенсивности. Результаты показали, что осадки вызывают значительные изменения в поровом давлении воды и снижают устойчивость откоса, при этом степень воздействия варьируется в зависимости от сценария. Среди них наибольшее дестабилизирующее влияние оказал сценарий с осадками умеренной интенсивности и продолжительного характера (Сценарий 3). Понимание того, как осадки влияют на поровое давление и коэффициенты безопасности откоса, имеет решающее значение для оценки устойчивости в условиях наихудшего сценария и разработки соответствующих эксплуатационных и профилактических мероприятий.

Ключевые слова: устойчивость откоса, влияние осадков на устойчивость откоса, численное моделирование, длительные осадки, оползень

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Вклад авторов: *Нгуен Х.Ф.Т.* — методология, программное обеспечение, написание текста; *Фам Н.Т.* — концептуализация, визуализация, написание текста — рецензирование и редактирование; *Нгуен Т.М.С.* — визуализация, написание текста — рецензирование и редактирование; *Нго В.Л.* — визуализация, написание текста, рецензирование и редактирование; *Данг В.Ф.* — проверка, надзор, концептуализация, написание текста, рецензирование и редактирование.

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1. Introduction

Slope instability, often manifested as landslides, poses a significant global threat, leading to substantial economic losses and, tragically, the loss of human lives. Among the various factors that can trigger slope failures, rainfall stands out as a primary catalyst. Intense rainstorms or prolonged periods of precipitation can significantly alter the hydrological and mechanical conditions within soil slopes, reducing their stability and increasing the likelihood of failure. The consequences of these events can be devastating, impacting infrastructure, disrupting communities, and causing widespread damage. Rainfall-induced slope failures are

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particularly acute in regions like Vietnam, characterized by a tropical monsoon climate with high rainfall intensity and prolonged wet seasons. The frequency of these events underscores the urgent need for comprehensive research to understand the underlying mechanisms and to develop effective prediction and mitigation strategies.

Numerous slope failures have occurred following heavy or prolonged rainfall events and have been documented in various studies [1–4]. These landslides often occur unexpectedly, and due to the absence of warning systems, they frequently result in significant human and economic losses. To understand the effects of rainfall on slope stability, numerous research articles have addressed this issue [1; 3–17].

Dang et al. [18] conducted a study evaluating the conditions and causes of landslides at Van Hoi Reservoir while considering environmental factors. In this research, the authors utilized survey measurements, experiments, and numerical simulations to assess slope stability. The study concluded that rainfall is one of the primary factors influencing landslides in this area. Additionally, rainfall alters the physical and mechanical properties of soil and pore water pressure, thereby impacting slope stability. However, this study examined the stability of natural slopes with highly permeable soil, which significantly differs from that of an earth dam. Tong et al. [9] investigated slope stability under the influence of prolonged rainfall using numerical simulations with GeoStudio software. This study demonstrated that rainfall significantly affects slope stability; with greater rainfall, slope stability decreases further. Rainfall patterns such as increasing intensity and uniform distribution have a more pronounced effect on slope instability compared to decreasing intensity and normal distribution scenarios. Nevertheless, in their study, the extreme rainfall and cyclical rainfall scenarios, similar to scenario 3 in this study, were not considered. Slope stability considering rainfall was also studied by Tran et al. [19] for natural slopes in Namyangju, South Korea. The authors indicated that under rainfall, negative pore pressure decreases, leading to reduced soil strength and an increased risk of instability. Additionally, the study highlighted the significant correlation between soil permeability and rainfall intensity affecting pore water pressure through the infiltration process. Rahardjo et al. [16] researched the impact of rainfall on slope stability with a five-day continuous rainfall scenario. Pore-water pressure was also examined under various rainfall scenarios, concluding that rainfall greatly affects slope stability. T.N. Pham et al. [10] studied the influence of different rainfall scenarios on slopes using numerical simulations. The authors found that both rainfall intensity and duration significantly affect pore water pressure and slope stability. Notably, in extreme rainfall scenarios with high intensity, the safety factor continues to decline after rainfall due to insufficient recovery time during the considered period. Despite various rainfall patterns being considered, the research focused on natural slopes only.

It can be seen that many studies have shown that rainfall infiltration increases pore water pressure and reduces slope stability. Nevertheless, while numerous studies have explored the impact of rainfall on embankments or primarily focused on natural slopes, research on the effect of rainfall on earth dam slopes remains limited. This limitation arises mainly because earth dams are constructed according to standards with relatively low permeability coefficients and high slope ratios, making the impact of rainfall on dam slopes less severe than on natural slopes. However, the impact of rainfall on the stability of an earth dam is still questionable and needs to be investigated. Because the safety of earth dams is a critically important task that requires careful and thorough consideration. Therefore, understanding the mechanisms of changes in pore water pressure and subsequent slope stability of earth dams after rainfall is essential for preparing measures to ensure the safety of reservoir dams, especially in areas prone to heavy rain. Accordingly, this paper focused on studying the impact of rainfall on changes in pore water pressure and the stability of earth dam slopes, using the Khac Khoan Reservoir earth dam case study in Bình Phuoc, Vietnam. The common rainfall patterns in the research area were also appropriately considered, particularly for the extreme conditions characterized by very high rainfall intensity and cyclical rainfall. To address these issues, this paper analyzed the effect of rainfall on pore-water pressure and slope stability utilizing the SEEP/W and SLOPE/W modules in GEOSTUDIO software.

2. Methodology

Seepage analysis aims to calculate the variations in pore water pressure within unsaturated-saturated soil slopes due to rainfall. The governing equation for seepage flow in homogeneous, isotropic soils is employed to analyze these pore pressure changes. The finite element method is utilized to simulate unsteady seepage processes within the slope using the SEEP/W module of the GeoStudio software.

$$\frac{\partial}{\partial x}\left(k_{\mathrm{x}}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_{\mathrm{y}}\frac{\partial h}{\partial y}\right)+Q=\left(\frac{\partial \theta}{\partial t}\right), \tag{1}$$

where h_w is the total head; k_x and k_y are the hydraulic conductivity in the *x*-direction and *y*-direction, respectively; *Q* is the applied boundary flux; *t* is time; θ is the volumetric water content of soil.

The Soil-Water Characteristic Curve (SWCC) is typically represented as the relationship between saturation, gravimetric water content, or volumetric water content and matric suction. In their study, Leong and Rahardjo [19] evaluated various empirical equations and concluded that the Fredlund and Xing [21] equation most accurately represents actual conditions, followed by the van Genuchten [22] equation.

$$\theta=\theta_r+\frac{\theta_S-\theta_r}{\left[1+\left(\frac{\psi}{a}\right)^n\right]^m}. \tag{2}$$

The Fredlund and Xing [21] equation is expressed as follows:

$$\theta=\theta_S C(\psi)\left\{\frac{1}{\left[\ln\left(e+\left(\frac{\psi}{a}\right)^n\right)\right]^m}\right\}, \tag{3}$$

where θ is the volumetric water content; θ_s is the saturated volumetric water content; θ_r is the residual volumetric water content; *C*(ψ) is the correction function; *e* is the natural number; ψ is the negative pore-water pressure; and *a, n, m* are the curve fitting parameters.

The factor of safety, according to the limit equilibrium method, can be calculated using either the moment equilibrium equation (F_m) or the force equilibrium equation (F_f) as follows [22]:

$$F_m=\frac{\sum\left[c'\beta R+\left\{N-u_w\beta\frac{\mathrm{tg}\phi^b}{\mathrm{tg}\phi'}+u_a\beta\left(1-\frac{\mathrm{tg}\phi^b}{\mathrm{tg}\phi'}\right)\right\}R\,\mathrm{tg}\phi'\right]}{A_L a_L+\sum \mathrm{W}x-\sum Nf}; \tag{4}$$

$$F_f=\frac{\sum\left[c'\beta\cos\alpha+\left\{N-u_{\mathrm{w}}\beta\frac{\mathrm{tg}\phi^b}{\mathrm{tg}\phi'}+u_a\beta\left(1-\frac{\mathrm{tg}\phi^b}{\mathrm{tg}\phi'}\right)\right\}\mathrm{tg}\phi'\cos\alpha\right]}{A_L+\sum N\sin\alpha}, \tag{5}$$

where *c’* is the effective cohesion; β is the length of the slice base; *R* is the radius of the circular slip surface; u_w is the pore-water pressure; ϕ*’* is the effective friction angle; ϕ_b is the change of shear strength with a change in suction; A_L is the external water force; a_L is the vertical distance from the center of the circular slip surface to the external water force; N is the total normal force at the base slice; f is the distance from the center of the circular slip surface to the normal force; u_a is the pore-air pressure; W is the weight of the slice; x is the horizontal distance from the center of the circular slip surface to the centerline of each slice.

3. Case Study

The case study is the earth dam at Binh Phuoc province, Vietnam, with the cross-section presented in Figure 1, and the soil properties are shown in the Table.

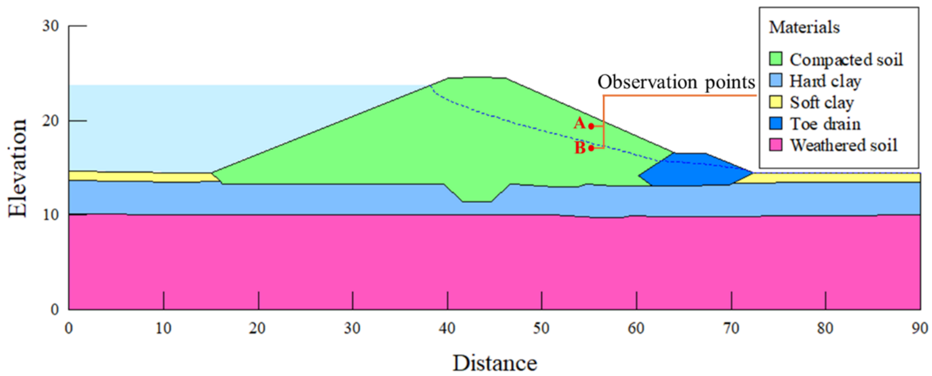

Figure 1. Cross-section of the earth dam at Binh Phuoc province, Vietnam
S o u r c e: made by H.P.T. Nguyen

Soil properties

Item	Symbol	Soft clay	Hard clay	Weathered soil	Compacted soil	Toe drain
Saturated soil unit weight	γ_{sat} (kN/m^3)	17.5	19.5	17.9	20.7	24.0
Unsaturated soil unit weight	γ_{unsat} (kN/m^3)	15.9	19.1	17.1	20.4	24.0
Effective cohesion	c' (kPa)	11	17	22	19	0
Effective friction angle	ϕ' (°)	11°13	15°32	17°21	16°11	36°
Saturated volumetric water content	θ_s (m^3/m^3)	0.741	0.477	0.569	0.561	–
Residual volumetric water content	θ_r (m^3/m^3)	0.01	0.01	0.01	0.01	–
Hydraulic conductivity	k (cm/s)	2.21E-04	3.50E-04	9.39E-05	4.50E-05	1.00E-03
Compressibility	m_w (kPa^{-1})	0.001	0.001	0.001	0.001	–

S o u r c e: made by H.P.T. Nguyen

In this area, extreme rainfall with a design frequency of $P = 0.5\%$ has an intensity of 300 mm/d. Based on this, four scenarios, illustrated in Figure 2, were considered in this study:

S c e n a r i o 1: No rainfall.

S c e n a r i o 2: Prolonged low-intensity rainfall with precipitation of 20 mm/d lasts for five days, then stops raining.

S c e n a r i o 3: Moderate rainfall with the intensity of 100 mm/d in one day, followed by a two-day cessation of rainfall; this cycle is repeated three times.

S c e n a r i o 4: Extreme rainfall with an intensity of 300 mm/d for one day, after which there is no further rainfall.

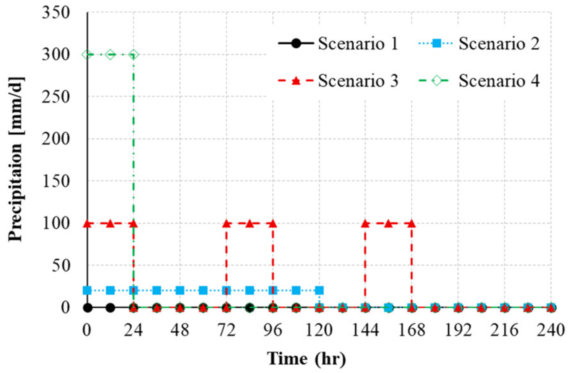

Figure 2. Four rainfall scenarios
S o u r c e: made by H.P.T. Nguyen

4. Results and Discussion

Two observation points, namely A and B, were spotted as shown in Figure 1. Point A was at 1 m depth from the ground surface and above the piezometric line, while point B was at 1 m depth below the piezometric line. In general, the pore-water pressure increased during rainfall and decreased when the rain stopped, as shown in Figure 3–5. These changes are more obvious for point A, which was located above the piezometric line and near the ground surface. It can be seen that an increase in pore-water pressure reduced the stability of the earth dam. In particular, under Scenario 3, the pore-water pressure shifted from negative to positive. After the rainfall stops, pore-water pressure tends to decrease, but the time required to return to its initial state is quite long. This behavior was observed in all three rainfall scenarios (2, 3, and 4).

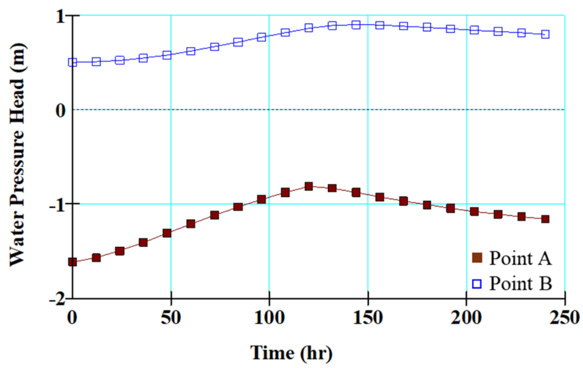

Figure 3. Pore-water pressure changes in Scenario 2
S o u r c e: made by H.P.T. Nguyen

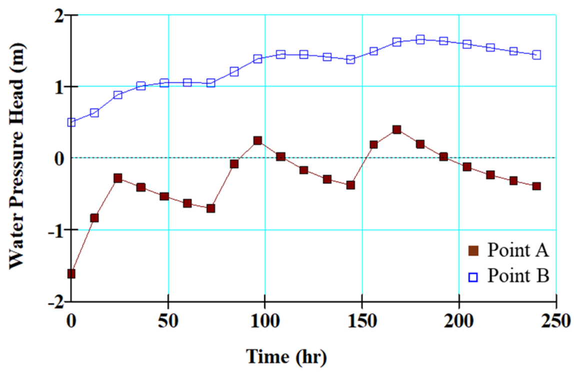

Figure 4. Pore-water pressure changes in Scenario 3
S o u r c e: made by H.P.T. Nguyen

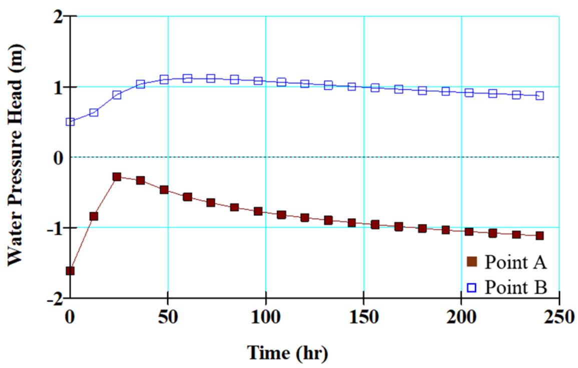

Figure 5. Pore-water pressure changes in Scenario 4
S o u r c e: made by H.P.T. Nguyen

Then, the slope stability analyses were conducted for four scenarios.

Figure 6 presents the critical slip surface at the initial condition, or Scenario 1. As can be seen from this figure, the factor of safety is 1.379, which is higher than the design value of 1.30. This implies the safety of this earth dam.

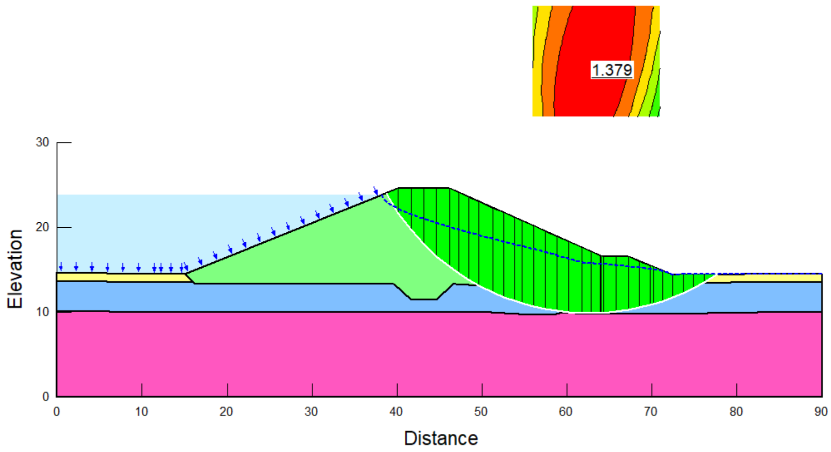

Figure 6. Slope stability analysis for Scenario 1
S o u r c e: made by H.P.T. Nguyen

The summary of results of the factor of safety by time histories for four scenarios is presented in Figure 7. In general, rainfall affects the stability of the earth dam, as proved by the decrease in the factor of safety during rainfall events. Furthermore, during rainfall events, larger rainfall intensity leads to a greater reduction in the safety factor. Prolonged rainfall with low intensity, as in Scenario 2, had a lesser impact on the stability of the dam slope compared to the other two rainfall scenarios. Scenario 3, characterized by moderate rainfall sustained over several cycles, significantly affected slope stability. This rainfall pattern is common in the southern provinces of Vietnam. Thus, in the design and construction of the earth dam, this type of rainfall should be carefully taken into account.

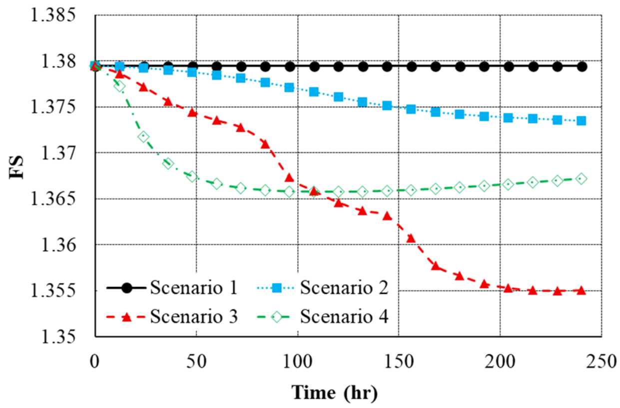

Figure 7. Slope stability analysis for four scenarios for ten days
S o u r c e: made by H.P.T. Nguyen

Specifically, for Scenario 2 with a rainfall intensity of 20 mm per day sustained over five consecutive days, the factor of safety gradually decreased, as shown by the blue line. However, this reduction was relatively minor, declining from 1.379 to 1.372. After the rainfall ceases, the factor of safety continued to decrease slightly, reaching 1.365 approximately three days post-rainfall, before beginning to increase again on the fourth and fifth days.

For Scenario 3, a rainfall with an intensity of 100 mm over 24 hours, followed by a 48-hour cessation of rainfall, repeated for three consecutive periods, markedly dropped the factor of safety from 1.379 to about 1.352, as indicated by the red curve. Notably, the two-day pause after each rain event was insufficient for the slope to recover its stability, which continues to decline.

For Scenario 4, with the intensity of 300 mm/day for one day only and then stops raining, the factor of safety dropped sharply and continued to decrease rapidly during the first day after rainfall cessation, as indicated by the green curve. It then continued to decline, but at a slower rate, on the second and third days without rain. After that, the stability of the earth dam began to recover, and the factor of safety increased gradually.

5. Conclusions

This paper investigated the influence of rainfall on soil pore-water pressure changes and the stability of an earth dam. Four scenarios with different rainfall intensities and durations were analyzed. From the results of this study, the following conclusions can be drawn:

1. In general, the impact of rainfall infiltration on the considered earth dam in this study is quite small when compared to natural slopes.
2. Rainfall increases pore water pressure of the earth dam, and the changes depend on both rainfall intensity and rainfall pattern.
3. Under Scenario 3, pore-water pressure transitions from negative to positive throughout the rainfall cycle. After the rain stops, pore-water pressure gradually decreases toward its pre-rainfall state, but the recovery is relatively slow.
4. Rainfall decreases the stability of the earth dam. The rate at which the factor of safety drops is directly proportional to rainfall intensity.
5. The severe condition is Scenario 3. The stability of the earth dam is significantly reduced compared to Scenarios 2 and 4.
6. Small rainfall, Scenario 2 (20 mm/day), the decrease in factor of safety is relatively slow, whereas under the extreme rainfall, Scenario 4 (300 mm/day), the reduction is much more pronounced. The factor of safety continues to decline for several days after rainfall ceases before beginning to recover.
7. Although the extreme rainfall of Scenario 4 causes a rapid initial drop in the factor of safety, the overall reduction is moderate compared to Scenario 3. Scenario 3 thus represents the most adverse condition studied and reflects rainfall patterns commonly experienced in southern Vietnam.

The findings enhance our understanding of the impact of rainfall on the stability of an earth dam, providing valuable guidance for design, operation, and maintenance under adverse conditions.

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