Infiltration Behavior of Hydrophobically Treated Slopes Under Extreme Rainfall

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ABSTRACT: As global warming accelerates, extreme rainfall events exceeding 50 mm/h have become more frequent, increasing the risk of rainfall-induced slope failures. Rapid infiltration during such events generates excessive pore water pressure, potentially leading to slope collapse. To mitigate this risk, hydrophobic soil treatment method has been proposed to reduce rainfall infiltration into slopes; however, experimental evaluations under extreme rainfall conditions remain limited. In this study, centrifuge model tests were conducted to investigate the infiltration behavior of hydrophobically treated slopes under extreme rainfall. A high-intensity rainfall simulator was developed and integrated into the centrifuge system, and the effects of rainfall duration and hydrophobic layer thickness on infiltration behavior were examined. The results show that hydrophobic treatment effectively reduces rainfall infiltration and suppresses pore water pressure development, thereby enhancing slope protection performance. These findings support the applicability of hydrophobic soil treatment as a countermeasure against rainfall-induced slope failures under changing climate conditions.

1 INTRODUCTION

Since the twentieth century, increased carbon dioxide emissions have led to a rise in global mean temperatures, resulting in a higher frequency of extreme weather events. According to a survey conducted by the Korea Meteorological Administration in 2021, South Korea's average annual temperature rose by 1.6°C from 1991 to 2020 (KMA, 2021). In addition, an analysis of 105 years of observational data for the Seoul region indicates that annual precipitation increased by 33.1 mm over the past decade (Lee et al., 2012). Recent rainfall trends show a general tendency toward shorter rainfall durations accompanied by increased rainfall intensity (Park and Seo, 2023). Such high-intensity rainfall can cause rapid infiltration into natural slopes, leading to a sudden reduction in slope stability and, in severe cases, substantial property damage and loss of life. Therefore, it is essential to investigate the infiltration behavior of slopes under extreme rainfall conditions and to develop effective mitigation techniques capable of suppressing rapid pore water pressure buildup.

In this study, a new slope protection technique utilizing hydrophobic soil materials was developed to minimize rainfall infiltration into slopes during extreme rainfall events. To evaluate its effectiveness on the slope stability under heavy rainfall, centrifuge model tests were conducted. Firstly, a rainfall simulator capable of reproducing extreme rainfall with an intensity of up to 90 mm/h under centrifugal acceleration was developed, and the infiltration behavior of an infinite slope treated with hydrophobic materials was experimentally investigated. Through these experiments, the slope protection performance of hydrophobically treated soil under extreme rainfall conditions was systematically verified.

2 DEVELOPMENT OF RAINFALL SIMULATOR

To simulate extreme rainfall during centrifuge model testing, a rainfall simulation apparatus was developed and installed above a soil container with internal dimensions of 295 mm × 500 mm × 200 mm (width × length × height), corresponding to a plan area of 0.10 m². The experiments were conducted using a small-scale geotechnical centrifuge with a rotation radius of 1,350 mm at Kangwon National University (Yoo et al., 1994).

The rainfall simulator was designed based on the rainfall similitude principles proposed by Tamate et al. (2012), which identify rainfall intensity (r), duration (t), droplet diameter (D), and terminal velocity (U) as the governing parameters under centrifugal acceleration (Table 1). Because terminal velocity and impact pressure increase with both centrifugal acceleration (Ng) and droplet size, a water–air mixed spray nozzle producing sufficiently fine droplets (BIMV 45075, Ikeuchi Co., Japan) was adopted. To further ensure realistic rainfall reproduction, the nozzle inclination angle was made adjustable to compensate for changes in droplet trajectory induced by the Coriolis effect during centrifuge rotation.

Table 1. Scaling law for rainfall (Tamate et al., 2012)

Permeability coefficient	**Rainfall amount**	**Rainfall intensity**
1	N*	1/N
Rainfall duration	**Terminal velocity**	**Droplet diameter**
N^2	$N^{1/2}$	N

* a multiple of gravitational acceleration

The prototype rainfall conditions were set to an intensity (r_p) of 90 mm/h and a duration (t_p) of 8 hours. Based on centrifuge scaling laws and the plan area of the soil container, the corresponding model-scale conditions were determined as a rainfall intensity (r_m) of 1 mm/s and a duration of 18 s. Sixteen nozzles arranged in a 2 × 8 configuration were installed to achieve uniform rainfall distribution over the model surface. In addition, the estimation method for raindrop terminal velocity under centrifuge conditions proposed by Mizuno (2003) was referenced in the design of the rainfall system:

$$U_m = C_{sc}\frac{{D_m}^2 Ng(\rho_w - \rho_a)}{18\eta_a} \quad (1)$$

Here, C denotes the Cunningham correction factor (C_{sc} = 1.02; Wright, 1995), D_m is the droplet diameter at the model scale, ρ_w and ρ_a are the densities of water (1000 kg/m³) and air (1.2 kg/m³), respectively, η_a is the dynamic viscosity of air (1.81×10^{-5} Pa·s at 20 °C), and Ng denotes N times the gravitational acceleration (9.81 m/s²). For a model-scale droplet diameter (D_m) of 20 μm under a centrifugal acceleration of 40g, the terminal velocity (U_m) was calculated as 0.49 m/s, corresponding to a prototype-scale terminal velocity (U_p) of 3.27 m/s.

Atlas and Ulbrich (1977) proposed the empirical relationship for raindrop terminal velocity as $U_p = 1{,}778 \times D_p^{0.67}$ (cm/s) for 0.5 mm ≤ D_p ≤ 5 mm. Assuming a prototype-scale droplet diameter of D_p = 800 μm, obtained from the centrifuge scaling relationship ($D_p = D_m \times N$ = 20 μm × 40), the resulting terminal velocity is U_p = 3.27 m/s. This confirms that rainfall similitude is satisfied under the selected conditions, and therefore the droplet diameter was controlled to be 20 μm or smaller.

Figure 1 illustrates the rainfall simulator for centrifuge model test. In the centrifuge tests, compressed air supplied from an external compressor was delivered to the rainfall apparatus through a rotary joint. The air supply was then divided by two pressure regulators and separately delivered to the spray nozzles (air pressure, P_a) and the water tank. By pressurizing the water tank, the water pressure (P_w) was controlled independently, allowing precise regulation of both air and water pressures. The regulated air and water were supplied to the nozzles through solenoid valves, enabling synchronized injection of air and water. Rainfall sprayed within the soil container was collected using a drainage tank installed beneath the container.

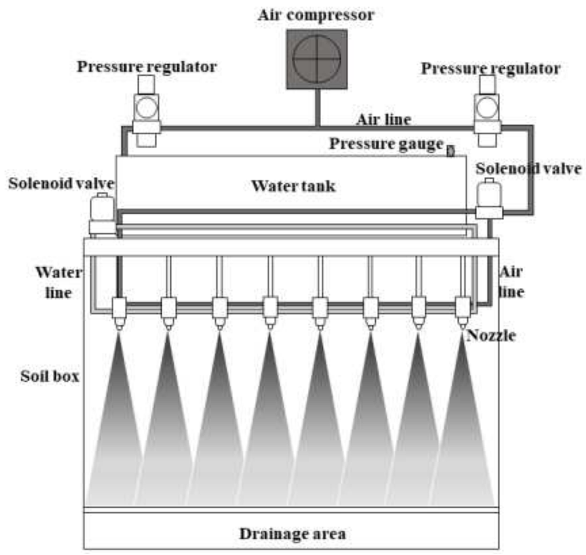


Figure 1. System diagram of rainfall simulator.

Considering the target rainfall intensity and duration, the experiments were conducted under air pressure P_a = 0.30 MPa and water pressure P_w = 0.15 MPa. To compensate for the Coriolis-induced deflection of droplet trajectories during centrifuge rotation, the nozzle spray angles were adjusted through repeated calibration tests. Based on these trials, the spray angles were set to 47.5° for the first nozzle row and 35° for the second row. Under these conditions, the spatial distribution of rainfall intensity at each measurement location is shown in Figure 2.

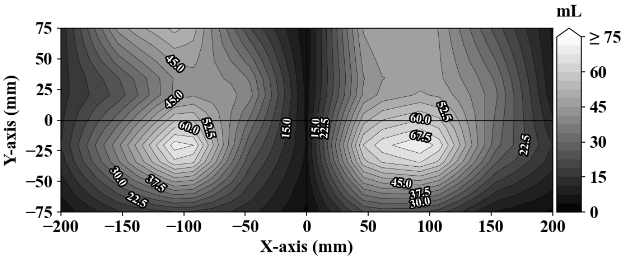


Figure 2. Rainfall distribution within the box (in model scale)

3 SOIL HYDROPHOBIC TREATMENT AND ITS PROPERTIES

Hydrophobic treatment is a surface modification technique in which wax-based or silane-based chemical agents are coated onto material surfaces to increase the water–particle contact angle, thereby suppressing pore water saturation and enhancing resistance to water infiltration. When applied to soil particles, this treatment inhibits the ingress of water into pore spaces and consequently reduces subsurface infiltration during rainfall events.

Hydrophobic soil preparation followed the procedure proposed by Kim et al. (2021), using Jumunjin sand (Table 2). The preparation process consisted of sample washing, chemical immersion, saturation, and drying. Prior to treatment, the sand was thoroughly washed to remove impurities and air-dried at room temperature. A hydrophobic solution was then prepared by mixing n-octyltriethoxysilane ($C_{14}H_{32}O_3Si$) with isopropyl alcohol (IPA) at a volumetric ratio of 1:99. For each 500 g batch of sand, 5 mL of n-octyltriethoxysilane and 495 mL of IPA were used. The sand was immersed in the solution for 72 hours and subsequently oven-dried at 110 °C for 24 hours to form a thin hydrophobic silane coating on the particle surfaces.

Prior to application in the centrifuge model tests, the hydrophobic performance of the treated sand was quantitatively evaluated using contact angle measurements and the water drop penetration time (WDPT) test (Kim et al., 2021). The specimens were prepared by pluviation into cylindrical glass containers with a diameter of 45 mm and a height of 30 mm, at a relative density of 80%. The specimen surface was carefully leveled, and the two tests were conducted sequentially on the same surface.

For the contact angle test, a water droplet was placed on the specimen surface using a dropper and immediately photographed. The contact angle (θ) was determined using image analysis software (Angle Meter). As shown in Figure 3, the measured contact angles ranged from 111.4° to 115.5°, exceeding the minimum criterion for hydrophobic behavior (θ > 90°) reported in previous studies (Bauters et al., 2000; Beckett et al., 2016; Kim et al., 2021; King, 1981; Movasat et al., 2021), thereby confirming successful hydrophobic treatment.

The WDPT test measures the time required for a water droplet placed on the soil surface to completely infiltrate or disappear. A penetration time exceeding 3600 s (1 h) is commonly regarded as indicative of hydrophobic soil behavior (Kim et al., 2021). The results showed that no noticeable change in droplet shape or volume was observed even after 1 hour, confirming that the WDPT exceeded 3600 s. Based on these results, the hydrophobically treated sand exhibited a minimum contact angle of 111.4° and a WDPT greater than 3600 s, demonstrating sufficient and stable hydrophobic performance for subsequent centrifuge model testing.

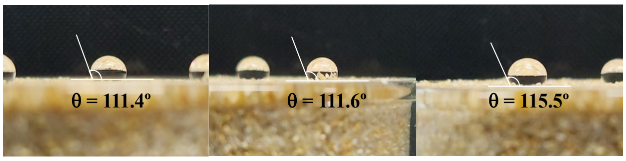


Figure 3. Contact angle of water droplet in the hydrophobic soil.

Table 2. Basic soil properties of Jumunjin sand

Properties	Values	Properties	Values
Specific gravity (G_s)	2.65	Max. dry density (g/cm^3)	1.66
Uniformity coefficient (C_u)	1.48	Min. dry density (g/cm^3)	1.33
Curvature coefficient (C_g)	0.96	Friction angle (°)*	43.7
D_{10} (mm) D_{60} (mm)	0.42 0.62	Friction angle of hydrophobically treated sand (°)*	37.9

* obtained from direct shear tests

4 CENTRIFUGE MODEL TESTS

4.1 Testing conditions

To evaluate slope infiltration characteristics under extreme rainfall conditions with the application of hydrophobic materials, centrifuge model tests were conducted on an infinite slope with an inclination of 1(V):1.8(H) (Figure 4). The prototype slope height was set to a maximum of 8 m, and the thickness of the soil layer was fixed at 3.2 m. The base of the soil layer was constructed to simulate bedrock conditions using an inclined polycarbonate (PC) plate. To ensure adequate shear resistance at the soil–bedrock interface, surface asperities were introduced, and #200 grit sandpaper was attached to the PC plate to enhance friction between the soil and the underlying acrylic block.

The overlying soil layer was formed using Jumunjin sand, representative of sandy soil behavior, and prepared by the air pluviation method. Sand was rained from a constant height into the soil container equipped with the simulated bedrock, achieving a uniform relative density (D_r) of 80%. After deposition, the surface was carefully trimmed to form the target slope geometry.

For experiments incorporating hydrophobic treatment, the sand ground was first prepared using the air pluviation method. A hydrophobically treated sand layer was then applied with a prescribed thickness to form the hydrophobic treatment layer. Since direct exposure of the hydrophobic layer at the ground surface may induce erosion under rainfall, an additional sand cover layer with a thickness of 0.4 m was placed above the hydrophobic layer to prevent surface scour.

The experimental variables were defined as the thickness of the hydrophobic layer and the rainfall duration (Table 3). In all tests, the rainfall intensity was maintained at a constant value of 90 mm/h. The thickness of the hydrophobic layer was varied as 0 m (untreated condition), 0.4 m, and 1.2 m, while rainfall durations of 4 h, 6 h, and 8 h were applied to experimentally investigate infiltration behavior under different conditions.

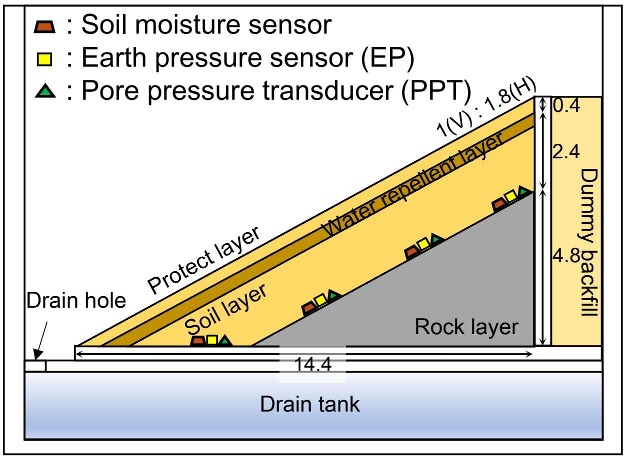


Figure 4. Model slope for centrifuge tests (unit: m).

To evaluate slope infiltration behavior under extreme rainfall conditions, earth pressure sensors, soil moisture sensors, and pore water pressure transducers were installed at regular intervals along the interface between the simulated bedrock and the soil layer. These instruments were used to monitor infiltration characteristics and hydromechanical responses of the slope during rainfall events.

Table 3. Testing conditions for centrifuge model tests

Case	C1	C2	C3	C4	C5	C6
Duration (h)	8			4	6	8
Repellent thickness (m)	0	0.4	1.2	0.4		
Intensity (mm/h)	90					
Soil thickness (m)	3.2					
Slope angle (V:H)	1:1.8					

4.2 Infiltration behavior according to hydrophobic layer thickness

Figure 5 presents the time history of volumetric water content measured at the slope toe from the onset of rainfall. Under all test conditions, infiltration initiated shortly after rainfall began, reached a maximum at the end of the rainfall event, and then smoothly dissipated rapidly once rainfall ceased. This rapid dissipation is attributed to the use of pure water, whose viscosity does not fully satisfy the centrifuge scaling requirement for soil permeability parameters. Nevertheless, a relative comparison remains valid.

Compared to the untreated condition (0 m, Case 1), the onset of infiltration under reinforced conditions (0.4 m, Case 2; 1.2 m, Case 3) was delayed by up to 1.29 hours immediately after rainfall initiation. This indicates that the hydrophobic layer effectively inhibited early-stage infiltration, demonstrating a short-term delay effect even under extreme rainfall intensity (90 mm/h). In addition, the reinforced condition with a 0.4 m hydrophobic layer (Case 2) exhibited a reduction in the peak volumetric water content relative to the untreated case.

In contrast, when a thicker hydrophobic layer was applied (1.2 m, Case 3), the maximum volumetric water content at the slope toe increased compared to the untreated condition (Case 1). This behavior is attributed to delayed drainage of infiltrated rainfall after passing through the hydrophobic layer, resulting in water accumulation near the slope base. These results indicate that an excessively thick hydrophobic layer may reduce drainage efficiency and adversely affect infiltration behavior.

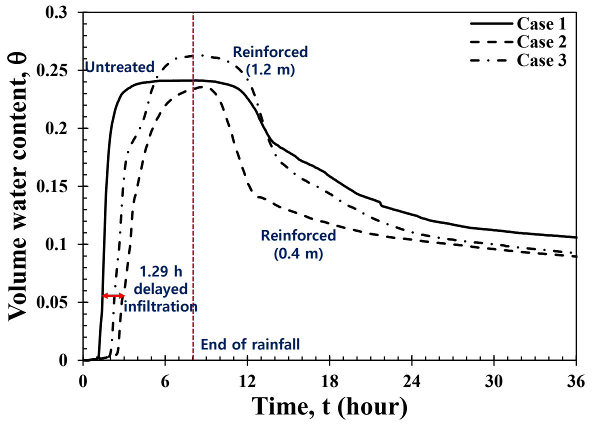


Figure 5. Effect of hydrophobic layer thickness on volumetric water content during rainfall.

Figure 6 illustrates the spatial distribution of volumetric water content within the slope with elapsed time after heavy rainfall. At 2 hours after the onset of extreme rainfall (90 mm/h), infiltration into the slope was effectively prevented under the reinforced conditions (Case 2 and Case 3). In contrast, the untreated condition exhibited elevated volumetric water content throughout the entire slope, indicating widespread infiltration across the cross-section.

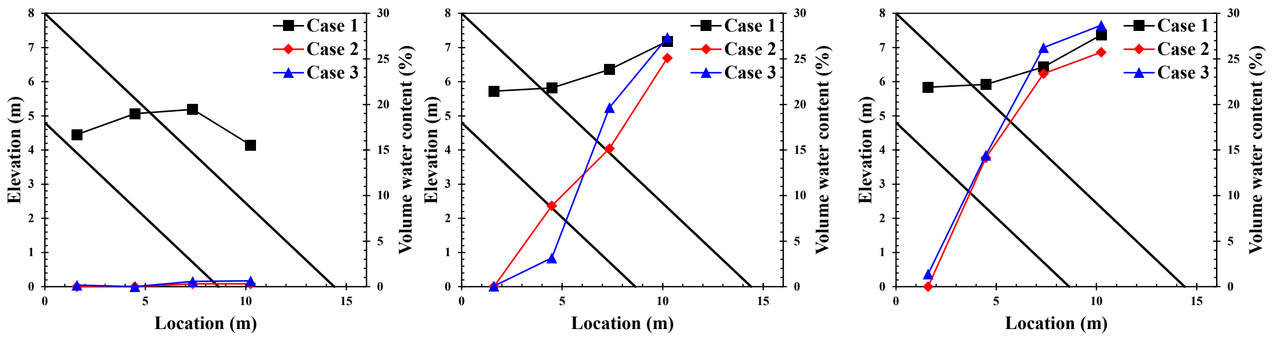
After 4 hours of rainfall, infiltration began to penetrate the hydrophobic layer even under reinforced conditions, and increased volumetric water content was observed primarily near the lower portion of the slope. When rainfall duration was extended to 8 hours, further infiltration occurred, resulting in a broader increase in volumetric water content. In the case of the thicker hydrophobic layer (1.2 m, Case 3), higher infiltration resistance was observed near the slope crest compared to the other cases; however, volumetric water content at the slope toe was significantly higher compared to Case 2 (0.4m). This phenomenon, consistent with the results shown in Figure 5, is attributed to insufficient drainage of water that had infiltrated through the hydrophobic layer.

These findings suggest that excessive thickness of the hydrophobic layer can reduce drainage capacity and potentially destabilize the slope under extreme rainfall conditions. Therefore, careful consideration is required when determining the thickness of hydrophobic treatment layers. Overall, the results confirm that the application of a hydrophobic layer can completely inhibit rainfall infiltration for more than 2 hours under extreme rainfall intensity of 90 mm/h. It was also confirmed that a hydrophobic layer with a thickness of 0.4 m provides superior drainage performance for infiltrated rainfall while maintaining infiltration resistance, compared to a thicker hydrophobic layer of 1.2 m.

4.3 Effects of rainfall duration on infiltration behavior

Figure 7 illustrates the variation of volumetric water content at the lower portion of the slope under the condition with a 0.4 m thick hydrophobic layer, measured after the onset of extreme rainfall. For all test cases, infiltration initiated at approximately the same elapsed time, indicating consistent infiltration onset behavior regardless of rainfall duration. In addition, the volumetric water content generally increased with increasing rainfall duration, reflecting the greater amount of rainfall infiltrating into the slope.

When rainfall duration exceeded 4 hours (Case 4), the maximum volumetric water content observed for the 6-hour (Case 5) and 8-hour (Case 6) rainfall conditions was similar, suggesting that the soil approached a saturated state after approximately 6 hours of rainfall. Following the end of rainfall, volumetric water content gradually decreased as drainage progressed toward the slope toe.



(a) t = 2 h **(b) t = 4 h** **(c) t = 8 h**

Figure 6. Variation of volumetric water content at different slope locations during rainfall.

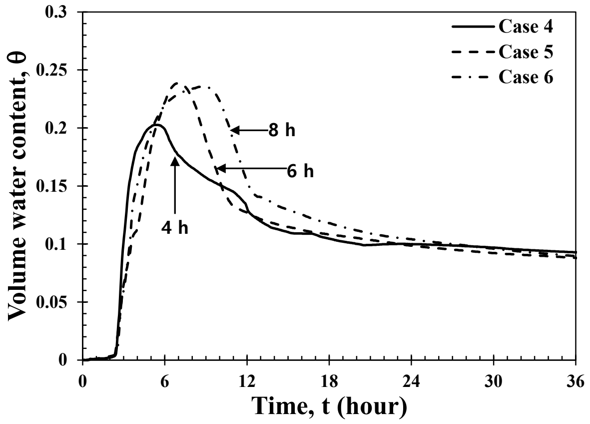


Figure 7. Variation of volumetric water content with rainfall duration.

Figure 8 presents the spatial distribution of volumetric water content along the slope at the end of the rainfall events. Higher volumetric water content was observed at the lower part of the slope, while progressively lower values were measured toward the upper slope. This behavior is attributed to partial infiltration occurring after the hydrophobic layer near the ground surface became fully saturated, allowing infiltrated rainfall to migrate downward and accumulate near the slope toe.

Notably, under the 4-hour rainfall condition, infiltration was effectively suppressed in the upper portion of the slope, confirming that the 0.4 m thick hydrophobic layer provides effective infiltration resistance for at least 4 hours under an extreme rainfall intensity of 90 mm/h.

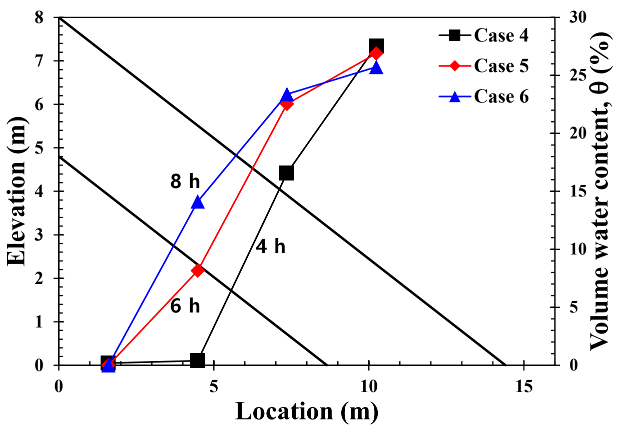


Figure 8. Distribution of volumetric water content with rainfall duration.

Overall, the results demonstrate that the application of a 0.4 m thick hydrophobic layer on the slope can maintain infiltration resistance for approximately 4 hours under extreme rainfall conditions (90 mm/h). However, when an excessively thick hydrophobic layer is applied, drainage of infiltrated rainfall may be impeded, potentially reducing slope stability. Therefore, careful determination of the optimal thickness of the hydrophobic layer is required.

Despite these findings, this study has several limitations. Infiltration similitude under centrifuge modeling was not fully satisfied, and the experimental conditions were limited to a specific rainfall intensity, hydrophobic layer thickness, and infinite slope geometry. In addition, the effects of successive rainfall events were not considered. Further studies are required to verify the applicability of the proposed approach under a wider range of conditions and to optimize the design of hydrophobic treatment layers for slope stabilization.

5 CONCLUSIONS

This study investigated the infiltration behavior of slopes incorporating hydrophobic materials under extreme rainfall conditions through centrifuge model testing. A rainfall simulator capable of reproducing prototype-scale extreme rainfall within a centrifuge environment was developed and implemented. Using this system, a series of centrifuge model tests were conducted to quantitatively assess the infiltration resistance and wetting delay effects induced by hydrophobic treatment of the slope under heavy rainfall conditions. The main findings of this study are summarized as follows:

- The application of a hydrophobic layer effectively delayed the onset of rainfall infiltration, with a maximum delay of approximately 1.29 hours compared to the untreated condition under an extreme rainfall intensity of 90 mm/h.
- A hydrophobic layer thickness of 0.4 m provided effective infiltration resistance for up to 4 hours of extreme rainfall while maintaining favorable drainage of infiltrated water.
- Excessive thickness of the hydrophobic layer (1.2 m) increased volumetric water content near the slope toe due to delayed drainage, indicating a potential adverse effect on slope stability.
- Under reinforced conditions, infiltration was initially suppressed across the slope, with localized infiltration occurring near the lower

slope as rainfall duration increased beyond 4 hours.

- Overall, the results demonstrate that appropriate selection of hydrophobic layer thickness is critical to achieving both infiltration resistance and drainage performance under extreme rainfall conditions.

However, infiltration similitude was not fully satisfied and the experimental conditions were limited; therefore, further studies under more diverse scenarios are needed to enhance applicability. For field implementation of engineered hydrophobic materials, large-scale production and installation methods, long-term durability, and resistance to repeated rainfall must be verified, along with appropriate measures to manage potential increases in surface runoff.

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