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Preliminary Experimental Investigation of Wetting Front Response in Slope Due to Tropical Rainfall Patterns

Enci Ng, Yuen Fong Hoo & Soon Min Ng*

School of Energy, Geoscience, Infrastructure and Society, Heriot-Watt University Malaysia, Putrajaya, Malaysia.

**Corresponding author: Soon_Min.Ng@hw.ac.uk*

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ABSTRACT

Intense and prolonged rainfall can lead to slope failure by increasing pore water pressure, which reduces effective stress and shear resistance. However, the impact of climate change has caused unpredictable rainfall patterns producing varying behaviour of wetting front and runoff. Thus, this study aimed to investigate the effect of tropical rainfall patterns on wetting front behaviour for soil slopes in Peninsular Malaysia using two-dimensional (2D) slope model with rainfall simulator. The rainfall patterns simulated were established based on 20 years historical rainfall data in Peninsular Malaysia recorded from year 2000 to 2020. The results revealed a positive correlation between rainfall intensity, duration, slope gradient, and wetting front responses. Higher rainfall intensity led to deeper wetting front progression on flat surfaces due to lower runoff and higher infiltration. Conversely, steep slopes experienced shallower wetting front progression due to the increase in surface runoff. In addition, an observed 42% increase in wetting front advancement on a 26° slope, corresponding to a change in rainfall pattern from five days 100 mm/hr to two days 420 mm/hr, illustrates a direct and significant correlation between increased rainfall intensity and the rate of wetting front propagation. 2. Therefore, integrating rainfall patterns into slope stability assessments can significantly improve the prediction of rainfall-induced failures and support the development of more robust and adaptive slope designs under varying hydrological conditions.

Keywords: Slope failure; wetting front; rainfall pattern; climate change

INTRODUCTION

Rainfall in tropical regions like Malaysia exhibits distinct patterns characterized by high intensity and significant variability. Such patterns can challenge the predictability and management of soil moisture dynamics (Douglas et al. 2008). In tropical climates, intense rainfall events are often followed by prolonged dry periods, complicating water management strategies and influencing the rates of infiltration and surface runoff (Chow et al. 1988). These intense and irregular rainfall events can saturate the soil quickly, overwhelming the infiltration capacity and leads to increase runoff that can cause erosion (Bruijnzeel 2004). Moreover, the rapid saturation of soil during intense rainfall can lead to reduction in matric suction, reducing soil strength and triggering slope failures (Idrus et al. 2023; Lu & Godt 2008).

As water penetrates the unsaturated zone of the soil, it moves downward through the pore spaces. This process creates a wetting front which is the boundary that separates the wetted soil and dry soil. This boundary is critical because it defines how water moves through the soil, affecting both the soil's physical structure and its hydraulic properties (Kirkham 2005). As water infiltrates the soil, it changes the hydraulic conductivity and matric potential along the wetting front, which can have significant implications for both natural and engineered soil systems (Bear 1972; Kirkham 2005). The progression of wetting front in soil can significantly affect the properties of the soil, reducing its stability and increasing the risk of failure (Lu and Godt 2008).

Malaysia is generally characterized by tropical climate and residual soil setting that is often unable to be simulated accurately by the existing infiltration models. For instance, Yao et al. (2022) noted that traditional models underestimate moisture content variations under non-uniform soil conditions, highlighting a significant gap in current hydrological modelling approaches. Additionally, the ongoing impact of climate change has complicated this issue further by altering precipitation patterns, necessitating adaptive models that can respond to evolving climate conditions to ensure infrastructure stability. (Morbidelli et al. 2018). The impact of varying rainfall intensities and durations on the wetting front's response and subsequent slope stability is also often neglected.

This research aims to bridge these gaps by utilizing empirical data collection approach in laboratory settings that replicate rainfall patterns on soil slope model representative of Peninsular Malaysia. By integrating real-time monitoring of soil moisture content, this study seeks to elucidate the behaviour of wetting front under tropical rainfall patterns. Such approach seeks to improve the resilience of both urban infrastructures by providing more reliable data for designing effective slope stabilization measures and drainage systems. The primary objective of this study is to examine the response of wetting fronts in tropical granitic residual soil slopes. To accomplish this objective, the study will first examine the characteristics of granitic residual soil and rainfall patterns prevalent in Peninsular Malaysia by analyzing 20 years of historical rainfall data. Secondly, it seeks to evaluate the response of wetting fronts within soil slopes through laboratory physical modeling. Finally, the general correlation between rainfall patterns and wetting front responses in tropical residual soil slopes will be established.

RAINFALL PATTERN OF PENINSULAR MALAYSIA

Daily rainfall data spanning from the year 2000 to 2020 sourced from the Department of Irrigation and Drainage were analyzed to examine the rainfall pattern in Peninsular Malaysia for the past 20 years. These data were recorded from 39 rain gauge stations distributed across various regions in Peninsular Malaysia as shown in Figure 1. It was found that Peninsular Malaysia receives a mean annual rainfall of approximately 2,500mm, indicating that the rainfall patterns have remained relatively consistent over the past two decades as shown in Figure 2. State-level analysis revealed that the mean annual rainfall in certain regions exceeds the average for Peninsular Malaysia. Notably, Terengganu recorded higher mean annual values of approximately 3,000 mm as shown in Figures 3.

FIGURE 1. Location of rain gauge stations for the 20 years rainfall data (DID, 2015)

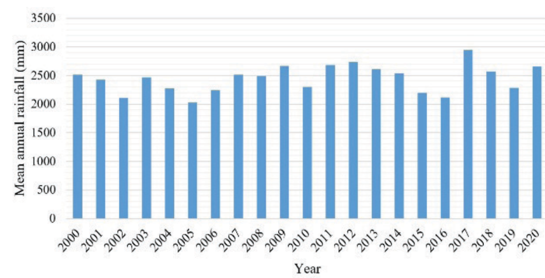

FIGURE 2. Average annual rainfall of Peninsular Malaysia for 20 years

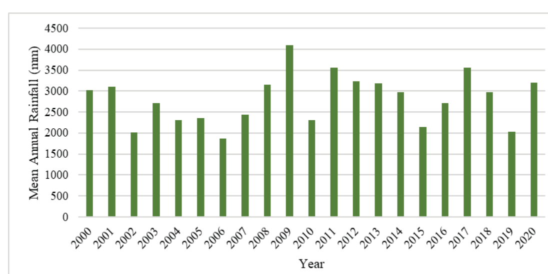

FIGURE 3. Average annual rainfall of Terengganu for 20 years

To investigate these changes in greater detail it is important to categorize the rainfall stations by region. The rain gauge stations can be divided into three primary regions based on their geographical locations namely Region 1 comprises states in the Northwest, Region 2 includes states from the Northeast, while Region 3 covers the Southern section of Peninsular Malaysia. From the 20 years rainfall data, it was found that the typical continuous rainfall recorded for Region 1 and 2 was 10 to 20 consecutive days whereas Region 3 typically experiences 8-15 days of consecutive rainfall. All three regions experienced the longest continuous rainfall of 30 to 40 consecutive days happening every 5 to 10 years. The extensive analysis over the last 20 years also revealed that Region 1 is susceptible to extreme weather events where 3 rain gauge stations recorded 13 occurrences of rainfall that last for 25 consecutive days or more.

A comparison study was also conducted by dividing the average annual rainfall data into 2 sets i.e. set 1 from year 2000 to 2009 and set 2 from year 2010 to 2020). Region 1 demonstrated a notable increase in rainfall, with a rise ranging from 9% to 22.4% when comparing set 1 and set 2 data except for Perlis recorded a reduction in rainfall of 2.9%. Conversely, Region 2 exhibited a more diverse trend, with Kelantan recorded an 11.4% increase in rainfall, while Terengganu has a more significant spike of 33.2%. Region 3 presents a varied situation where Pahang and Melaka have recorded a reduction in rainfall of 4.2% and 11.6%, respectively. In contrast, the other states in Region 3 recorded a rainfall increase from 7.7% to 17.1%. Table 1 summarized the changes in average annual rainfall for Peninsular Malaysia between year 2000-2010 and year 2010-2020. Overall, these results indicated that the annual total rainfall in Peninsular Malaysia is showing a rising trend over the last 2 decades that may increase the frequency of slope failures.

One significant limitation for this study is that only total daily rainfall was available for the 20-year period with no detailed hourly measurements recorded by the automated rain gauges. However, the maximum daily rainfall is considered adequate for estimating various rainfall intensities by dividing it over specific durations. Although this method assumes a uniform distribution of rainfall throughout the day, it still offers a reasonable approximation of critical conditions, especially when compared against historical slope failure records that reflect similar rainfall-triggered events. Table 2 presents the maximum daily rainfall recorded in Peninsular Malaysia from year 2000 to 2020. From these data, it was found that Region 2 experienced the highest daily rainfall with an average of 439 mm/day followed by Region 3 with 274 mm/day and Region 1 with 241 mm/day.

TABLE 1. Changes in average annual rainfall between 2000-2010 and 2010-2020 (DID, 2015)

Region 1	Change in average annual rainfall (%)	Region 2	Change in average annual rainfall (%)	Region 3	Change in average annual rainfall (%)
Perak	22.4	Kelantan	11.4	Johor	15.7
Kedah	4.9	Terengganu	33.2	Pahang	-4.2
P. Pinang	9.00			Melaka	-11.6
Perlis	-2.9			N. Sembilan	17.1
				Selangor	7.7
				Kuala Lumpur	8.3

TABLE 2. Maximum daily rainfall recorded in Peninsular Malaysia from year 2000 - 2020

Region	States	Rainfall per day (mm)	Date	Mean Annual Rainfall (2000-2009)	Mean Annual Rainfall (2010-2020)
1	Kedah	305.5	July 2002	3155.66	3310.96
	Perak	232.2	Nov 2011	2108.42	2580.41
	Perlis	149.1	Sept 2017	1869.67	1815.59
	P. Pinang	276.5	Sept 2017	2707.36	2950.56
2	Kelantan	540.5	Dec 2014	2291.04	2553.77
	Terengganu	337.4	Dec 2018	2626.93	3499.67
3	Johor	477.8	Dec 2019	2581.04	2986.07
	Kuala Lumpur	154.9	Jan 2013	2364.2	2559.78
	Melaka	141.5	Jan 2011	1818.02	1606.87
	N. Sembilan	252	Nov 2020	2234.7	2615.93
	Pahang	424.2	Jan 2017	2765.99	2649.86
	Selangor	194	Nov 2004	2302.69	2480.51

LABORATORY MODELLING

TWO-DIMENSIONAL (2D) SLOPE MODEL

Experimental study using the two-dimensional (2D) slope model with rainfall simulator was conducted to investigate the response of wetting front under rainfall. As illustrated in Figure 4, the 2D slope model was constructed using acrylic Perspex that measures at 1.2m length, 0.6m height, and 0.35m width. The rainfall simulator consisted of four nozzles mounted on a PVC pipe positioned at 0.4m above the soil surface. The water pump, connected to a reservoir, provides continuous water supply and the rainfall intensities can be regulated by the flowmeter. Furthermore, the 2D slope model is also designed to enable modification of the slope angle by using the hydraulic jack system. This feature is essential to evaluate the impact of varying rainfall intensities and slope angles on wetting front response. To enable soil moisture monitoring during the experiment, holes were made at the sides of the slope model to allow the insertion of soil moisture probe. Lastly, a discharge outlet was made to enable runoff measurements simulating the actual field condition.

The soil water content was measured by the sensors known as Trime-Pico32 probe supplied by IMKO as shown in Figure 5. This probe utilized the Time Domain Reflectometry (TDR) technology that operates on the principle of emitting a time-domain signal into the soil through probe rods, and then measuring the time it takes for the reflected signal to return. The TDR sensors, thus, enable the quantification of soil moisture by correlating the measured dielectric constant with moisture content, offering a non-destructive and accurate method for in situ moisture analysis (Robinson et al. 2003). One of the key features of TDR technology is its ability to provide real-time, continuous monitoring of soil moisture, which is essential for various applications such as agricultural management, hydrology, and climate studies (Jones and Or, 2004). The TDR probe was calibrated prior to the experiment to ensure the soil moisture measurements are accurate and reflective of the actual moisture content (Skierucha et al. 2008).

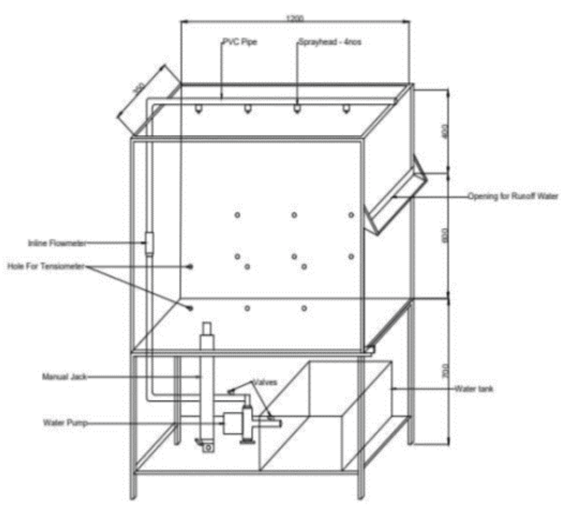

FIGURE 4. 2D slope model with rainfall simulator apparatus

FIGURE 5. Trime-Pico32 TDR probe

COLLECTION AND PREPARATION OF SOIL SAMPLES

Soil samples were collected from a granitic residual soil slope located at Banting, Selangor. Sieve analysis was conducted on soil samples to determine the particle size distribution in accordance with BS EN ISO 17892-4:2016. Hydrometer test was also conducted because the sample has more than 10% of particle sizes smaller than 0.063 mm. Based on the particle size distribution, the soil sample is classified as well-graded sand. Constant head permeameter test was also carried out in accordance with BS EN ISO 17892-11:2019 to determine the hydraulic conductivity of the soil sample. Table 3 summarized the geotechnical properties of the soil sample.

PARAMETRIC STUDY

The soil sample was filled and compacted in the slope model according to the bulk density value. The moisture content of the soil is maintained as its natural moisture content of about 4% to 15% to replicate the field condition. This moisture content is again verified before the start of the experiment by using the TDR probes. A mixture of coarse aggregate and well graded soil of about 250 mm thickness was placed at the base layer to minimize the amount of soil sample to be used as shown in Figure 6. Prior to the experiment, the flow meter to regulate the pumping system was calibrated to ensure the produced rainfall is accurate to the required value.

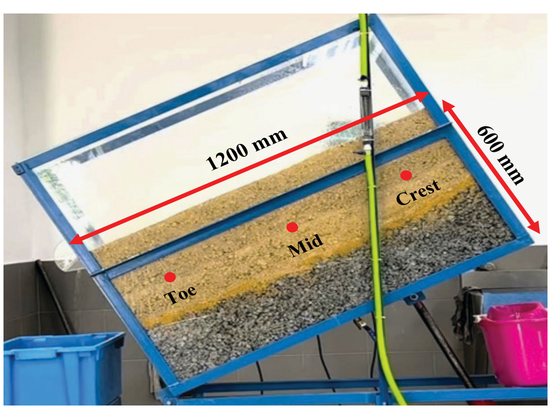

FIGURE 6. Experimental investigation set up

Table 4 summarized the parametric studies that were conducted to investigate the influence of rainfall intensity and slope angle on the response of wetting front. This experimental design was chosen based on 20 years rainfall data recorded from Terengganu, which recorded the highest cumulative rainfall of 840 mm over a 5-day period. This critical amount of rainfall that may trigger slope failure was categorized into the following experimental rainfall pattern: i) high intensity long duration at 0° slope (E1), ii) high intensity long duration at 26.6° slope (E2), iii) high intensity short duration at 26.6° slope (E3), and iv) low intensity long duration at 26.6° slope (E4).

TABLE 3. Geotechnical properties of soil sample

Properties	Value
Percentage of sand (%)	84
Percentage of silt (%)	15
Percentage of clay (%)	1
Hydraulic conductivity (m/s)	9.5×10^{-6}
Moisture content (%)	13
Bulk density (kN/m^3)	14.5
Friction Angle (°)	30
Cohesion (kPa)	3

TABLE 4. Summary of design of experiment

High intensity long duration 0° slope (E1)		
Day	Intensity (mm/hr)	Duration (min)
1	140	60
2	220	60
3	140	60
4	240	60
5	100	60
High intensity long duration 26.6° slope (E2)		
Day	Intensity (mm/hr)	Duration (min)
1	140	60
2	220	60
3	140	60
4	240	60
5	100	60
High intensity short duration 26.6° slope (E3)		
Day	Intensity (mm/hr)	Duration (min)
1	420	60
2	420	60
Low intensity long duration 26.6° slope (E4)		
Day	Intensity (mm/hr)	Duration (min)
1	100	60
2	100	60
3	100	60
4	100	60
5	100	60

RESULTS AND ANALYSES

OBSERVATION OF WETTING FRONT

Comparing the experiment between high-intensity rainfall on flat surface (0°) and sloping ground (26°), the results demonstrated that the wetting front progresses significantly faster and penetrates deeper on flat ground than on the slope as illustrated in Figure 7. This is attributed to lesser runoff on flat surface that leads to higher infiltration. Experiments on 26° slope terrain reveal a distinct disparity in the progression of wetting front between high and low rainfall intensities. At high intensity rainfall, the wetting front progressed deeper compared to low intensity. This result indicates that despite the increase in runoff potential due to the sloping ground, higher intensity rainfall produced higher volume of water that is able to infiltrate into deeper soil. It was also observed during the experiment that the wetting front progression rate is higher at the toe of the slope due to the accumulation of runoff before being discharged out of the model. This is because the movement towards the toe may occur from both the gravitational force on the water and the slope's geometry, which inherently drives water flow downslope, thus increasing saturation at the toe.

Across the experiments, higher rainfall intensities consistently surpassed both the depth and speed of the wetting front compared to the lower intensity conditions on a 26° slope. This suggests that higher volumes of water can overcome the gravitational pull associated with slopes more effectively, allowing for deeper and faster infiltration before significant runoff occurs. It is noted that the increase in the wetting front depth is initially rapid at the commencement of rainfall but decelerates as time progresses as presented in Figure 8. This phenomenon is mainly due to the initial partially saturated state of the soil that helps water to flow through soil easily. As the soil becomes saturated, the rate of infiltration decreases (Wei et al. 2022).

Based on observation, a correlation between rainfall intensity and the rate of wetting front progression can be established as shown in Table 5. The advancement rate on a 26° slope increases from 70 mm/hr for 100 mm/hr rainfall to 100 mm/hr for 420 mm/hr rainfall. This 42% increase in wetting front progression clearly demonstrates that heightened rainfall intensity and duration can markedly accelerate the advancement of the wetting front. This outcome also highlights the significance of including rainfall intensity in hydrological and geotechnical evaluations, as it profoundly influences soil moisture dynamics and slope stability.

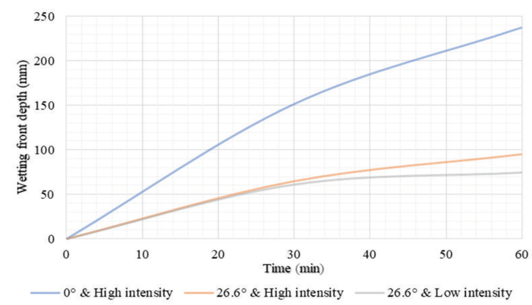

FIGURE 7. Wetting front progression depth against time

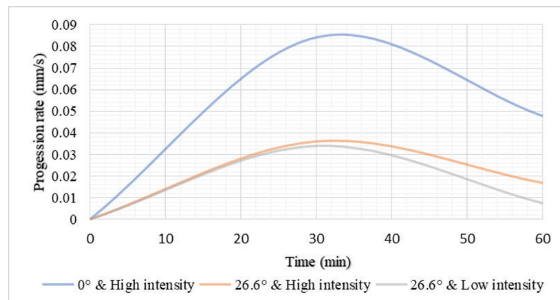

FIGURE 8. Rate of wetting front

TABLE 5. Progression rate of wetting front

Experiment	Rate of Progression (mm/hr)
E3	100
E4	70

ANALYSIS OF MOISTURE CONTENT

The changes in soil moisture content at three different locations in relation to different rainfall patterns were recorded by TDR. For experiment E1, the graphs illustrate pronounced peaks in moisture content corresponding to each rainfall event as shown in Figure 9. Due to the horizontal surface, the TDRs monitoring points are located at the same level, thus exhibiting similar moisture content pattern change. The peaks indicate instantaneous saturation from the rainfall, followed by reductions in moisture content as the water infiltrates and drains. Nevertheless, the moisture content does not completely revert to baseline values, signifying a certain degree of water retention within the soil. This retention is primarily due to capillary forces that trap water within the soil pores. As a result, pore water pressure increases, which in turn reduces the effective stress acting within the soil matrix. This reduction in effective stress weakens the soil's shear strength, thereby elevating the risk of slope failure. At the first rainfall event, the moisture content increased by 11% from 10% to 21%. The increment of moisture content reduced greatly to about 6% from 15% to 21% during the subsequent rainfall events.

Figures 10 and 11 present the high-intensity rainfall on 26.6° inclined slope for long and short duration. Both results illustrated pronounced peaks in moisture content corresponding to rainfall events, particularly at the toe. The peaks indicate instantaneous saturation from the rainfall, followed by reductions in moisture content as the water infiltrates and drains. It was also observed that some moisture remained in the soil following each rainfall event, as indicated by the moisture content not returning to its baseline values similar to experiment E1. Significant differences in moisture content were observed along the slope, with the toe persistently exhibiting greater saturation, likely due to the downward migration and accumulation of water from upslope areas.

The results for low intensity long duration rainfall on 26.6° inclined slope as shown in Figure 12 reveal a lesser increase in moisture content. In contrast to the abrupt increases observed after intense rainfall, the moisture content for low intensity rainfall rises gradually, indicating lower infiltration rate. The toe of the slope is consistently identified as the critical zone, where moisture content plateaus, indicating saturation. This condition leads to a reduction in shear strength, thereby increasing the likelihood of slope failure. The difference graph further underscores this point, showing that the toe experiences a steady increase in moisture, likely due to its position and the extended duration of rainfall allowing for more pronounced lateral water movement.

Across all scenarios, it is evident that the toe of the slope is most vulnerable to elevated moisture content, demonstrating the combined impacts of vertical and lateral water flow, along with soil properties that may impede effective drainage. The variations of moisture content and water retention after successive rainfall events underscore the necessity of incorporating these variables in slope stability assessment.

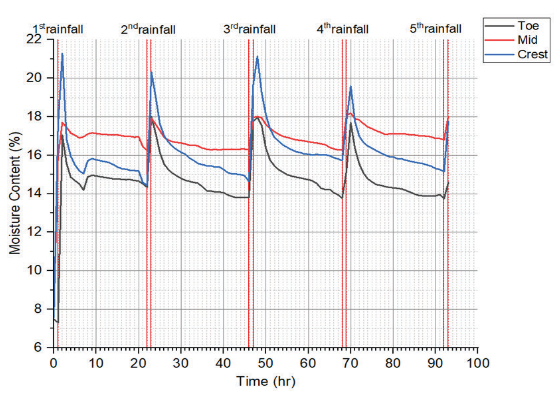

FIGURE 9. Moisture content record for 5-day high intensity rainfall (0° slope))

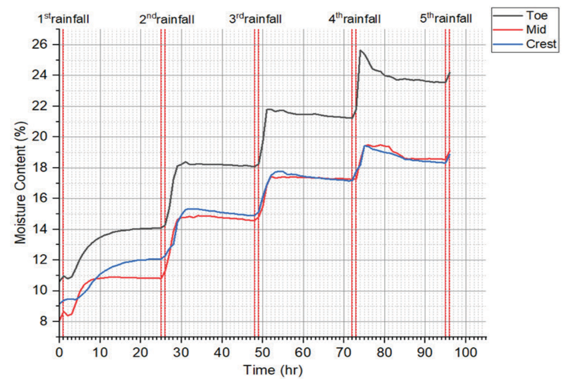

FIGURE 10. Moisture content record for 5-day high intensity rainfall (26.6° slope)

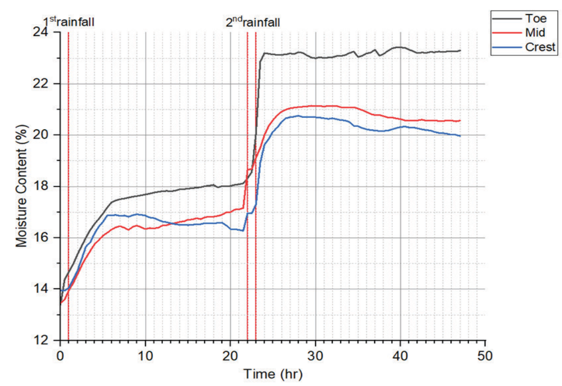

FIGURE 11. Moisture content record for 2-day high intensity rainfall (26.6° slope)

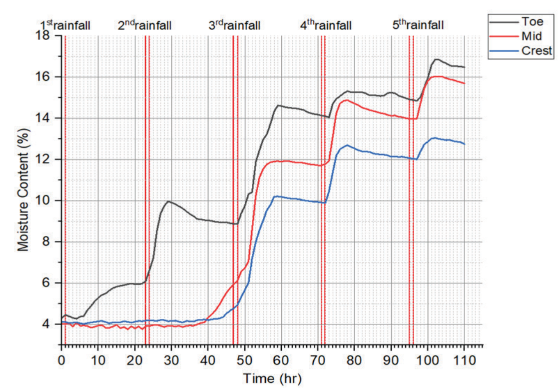

FIGURE 12. Moisture content record 5-day low intensity rainfall (26.6° slope)

CONCLUSION

The research employed extensive rainfall data from the Department of Irrigation and Drainage to examine the impact of climate change on the changes in rainfall patterns over a 20-year span. The comprehensive climatic analysis of the three main regions reveals distinct rainfall trends:

Region 1 exhibits a significant increase in both rainfall volume and duration, Region 2 displays variability with pronounced differences among areas, and Region 3 shows a mixed scenario with both increases and decreases in rainfall amounts. The observed extended rainfall, especially in Region 1, which has recorded numerous extreme weather incidents, indicates a heightened frequency of such occurrences during the past two decades. The variation in rainfall duration amongst the regions, with Region 1 and 2 averaging from 10 to 20 days and Region 3 from 8 to 15 days are now experiencing prolonged rainfall events of 30 to 40 days, indicating the evolving weather patterns.

The examination of both wetting front progression and moisture content variations offered preliminary insights of soil hydrological responses to rainfall events. Higher rainfall intensity can increase the wetting front progression rate and depth by approximately 40% compared to low rainfall intensity. These insights reveal that high-intensity rainfall that is expected to become more frequent and severe due to climate change can rapidly saturate soil slopes despite high amount of runoff. Such elevated saturation increases the risk of slope failure highlighting the importance of incorporating changing rainfall patterns into slope stability assessments. This approach enables the development of safer, climate-resilient slope management systems that proactively address geohazard risks in an evolving climatic condition.

This study will be further extended to include different soil gradation, higher slope gradient and extra variation on rainfall patterns to establish a distinct correlation for slope stability prediction. Additionally, numerical analysis will also be employed to verify the experimental results and provide supplementary findings on the dynamic and complex interactions between rainfall pattern and soil behaviour.

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DECLARATION OF COMPETING INTEREST

None.

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