INFLUENCE OF RAINFALL AND SOIL-WATER CHARACTERISTIC CURVE ON SLOPE STABILITY FOR UNSATURATED SOIL: CASE STUDY AT ROUTE 14G, DANANG, VIETNAM

Le Manh Thuong, Dinh Minh Tran*, Tran Trung Viet

The University of Danang - University of Science and Technology, Vietnam

*Corresponding author: tdminh@dut.udn.vn

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Abstract - This study utilizes Geo-Slope 2D to evaluate slope stability along Route 14G, integrating soil characteristics and historical rainfall data to analyze the slope stability based on the Factor of Safety (FoS). Key findings highlight the significant role of Soil-Water Characteristic Curves (SWCCs) and permeability coefficients in determining slope responses to varying rainfall levels. Soils with higher permeability coefficients, like clayey soil 3, exhibit more rapid decreases in FoS, leading to earlier instability. The result identified a critical rainfall threshold associated with slope failure, highlighting that instability can occur before the soil is fully saturated, challenging conventional assumptions. These insights underline the importance of considering soil suction and shear strength in slope stability assessments. The findings provide essential references for developing effective landslide mitigation strategies tailored to the specific vulnerabilities of the region, thereby enhancing the safety and resilience of slopes along Route 14G.

Key words - Factor of Safety; rainfall; slope stability; Soil-Water Characteristic Curves; unsaturated soil.

1. Introduction

Landslides on earthen slopes following prolonged rainfall due to climate change have become increasingly severe [1]. This phenomenon becomes particularly serious in areas with earthen slopes as the soil structure is weak and prone to landslides [2]. Each time there is prolonged rainfall, the accumulated water on the earthen slope can increase suddenly, making slopes unstable and susceptible to landslides [3]. The consequences of landslides on earthen slopes include loss of life and property and impacts on local communities' economy and infrastructure [4]. With the growing complexity of climate change, extreme weather events like prolonged heavy rainfall are expected to become increasingly severe and dangerous [5]. Consequently, it is crucial to examine, analyze, and assess the stability of earthen slopes to ensure the safety and stability of the community.

One of the reasons leading to serious consequences of landslides after rain is that in assessing slope stability, the impact of rainfall on the area is often not comprehensively considered. Previous studies have focused on factors such as slope steepness, soils, and geological structures, ignoring the influence of rainfall [6-8]. However, rain can have many negative effects on terrain stability. Heavy rainfall can exert strong pressure on the ground, making it unstable and increasing the ability of water to seep into the soil, resulting in it being softer and more susceptible to landslides [9]. In addition, rain can increase the water load on inclined surfaces, creating push and pull on the ground, leading to movement and landslides [10].

In the analysis of slope stability under the influence of rainfall, current studies are utilizing the soil-water characteristic curve (SWCC) model proposed by Fredlund and Xing [11], and Genuchten [12] to determine the distribution of moisture and water pressure within the earthen slopes. Globally, numerous research endeavors have demonstrated the flexibility of this model by adjusting and applying it to diverse geographies and soils. The results reveal that the appropriate selection of the SWCC model can significantly impact the Factor of Safety (FoS) of slopes, especially when considering factors such as terrain, soil characteristics, and rainfall [13]. It is well-established that variations in these fundamental soil properties can trigger substantial alterations in the soil's capacity to resist shearing forces directly impacting slope stability [14].

The empirical insights garnered from previous research underscore compelling trends. Initially, during periods of low precipitation, it observes a notable augmentation in soil cohesion and shear strength owing to the elevated water pressure within the soil matrix. This phenomenon accentuates the stability of slopes and fortifies their resistance against potential failure mechanisms [15]. However, as precipitation intensifies, the dynamics shift with increased water pressure poses a contrasting effect on soil shear strength. The influx of moisture serves to undermine the cohesion of the soil, thereby compromising its ability to withstand shearing forces. Consequently, this increasing rainfall-induced instability highlights the failure susceptibility of slopes [16].

This research focuses on analyzing the effect of rainfall on the stability of unsaturated slopes at Route 14G in Da Nang. To unravel the complexities underlying this phenomenon, we have employed a 2D Geo-Slope model, recognized for its efficacy in simulating geotechnical scenarios, to examine the stability of slopes. Our methodological approach applied soil-water characteristic curves (SWCCs) of three soils derived from earthen slopes along Route 14G. Furthermore, our investigation extends beyond static analyses by integrating considerations of rainfall variability, a crucial factor of slope stability assessments.

2. Research parameters at Route 14G

2.1. In-site location

The research area along Route 14G, located to the West of Da Nang City, Vietnam (see Figure 1), urgently requires in-depth investigation due to its pronounced vulnerability to geological erosion. This issue has persistently recurred during the rainy seasons from 2020 to 2022, and its persistence underscores the need for a focused study.

Figure 1. *Landslide phenomenon on Route 14G*

The region's susceptibility to erosion is linked to its geographical and geological characteristics, such as steep slopes, loose soil, and frequent heavy rainfall. These factors have led to significant landslides, where large sections of soil and rock have become dislodged and slid down, posing a continuous threat to the area. The landslides have resulted in substantial soil and rock overflow onto the roadway, severely complicating ongoing construction efforts. This obstruction not only hinders progress but also forces workers to allocate additional time and resources to clear the debris and soil, which in turn delays the construction schedule and incurs increased costs due to the need for repeated cleanup and stabilization. In addition, the loose soil and rock increase the risk of future landslides, making the area increasingly unstable and hazardous for construction workers and future road users.

2.2. Physical and mechanical parameters

In recent studies in Vietnam, it has been pointed out that most of the land in Da Nang is clayey soil [17, 18]. Table 1 summarizes the physical parameters of three clayey clayey soils along Route 14G. Table 1 provides a comprehensive comparison of various physical parameters among the three clayey soils and illustrates that the natural moisture content of all three soils does not significantly differ, ranging from 25.3% to 26.95%. Similarly, other parameters such as natural density, dry density, porosity, void ratio, and saturation degree exhibit similar values across the samples. However, the saturated permeability coefficient (k_{sz}) of clayey soil 1 has the smallest value at $k_{sz} \sim 2.84\times10^{-6}$ cm/s, followed by clayey soil 2 and clayey soil 3 with values of $k_{sz} \sim 3.78\times10^{-5}$ cm/s and $k_{sz} \sim 6.24\times10^{-5}$ cm/s, respectively. The internal friction angle increases sequentially to 14.6, 20.1, and 26.7 degrees, while the cohesion of clayey soil 2 is the lowest with a value of 8.1, followed by clayey soil 3 at 14.5 and clayey soil 1 at 16.9.

Table 1. *Physical and mechanical parameters of three clayey soils [17, 18]*

Parameter	Symbol	Unit	Clayey soil 1	Clayey soil 2	Clayey soil 3
Moisture content	W	%	26.95	25.30	26.13
Wet density	γ	kN/m^3	18.8	18.9	19.2
Dry density	γ_d	kN/m^3	14.8	15.1	15.2
Void ratio	e	-	0.824	0.781	0.770
Porosity	n	%	45.18	43.85	43.50
Saturated degree	S	%	88.3	87.14	91.3
Internal friction angle	φ	độ (^{o})	14.6	20.1	26.7
Soil cohesion	C	kPa	16.9	8.1	14.5
Permeability coefficient	k_{SZ}	cm/s	2.84×10^{-6}	3.78×10^{-5}	6.24×10^{-5}

2.3. SWCC and permeability coefficient

The experimental results of SWCCs for the three clayey soils are synthesized in Figure 2, providing a comparative analysis of their soil-water interaction behaviors [17, 18]. These findings reveal notable variations in the SWCCs of the three clayey soils, despite their apparent similarity in classification as clayey soils. Specifically, clayey soil 3 exhibits the lowest suction among the soils, indicating a lower capacity to retain water under unsaturated conditions. In contrast, clayey soil 1 rapidly progresses to saturation, absorbing water quickly and reaching a saturated state faster than the other soils.

This analysis is significant as it underscores the critical need to understand the variations in SWCC among soils that may initially appear similar. These differences in soil-water interaction behavior can be attributed to various factors. For instance, pore structure plays a pivotal role, as soils with larger or more interconnected pores may allow water to move through more easily, influencing suction and saturation levels. Mineral composition is another crucial factor, as certain minerals can affect a soil's ability to retain or absorb water. Additionally, the history of the soil, including its formation, weathering processes, and previous exposure to environmental conditions, can also impact its SWCC.

In addition to the analysis of SWCC, we examined the soil permeability coefficients under cohesive suction conditions, as shown in Figure 3. This aspect of the study is crucial because it highlights the significant role that cohesive forces play in influencing the permeability of soils, particularly in cohesive soil types such as clay. Cohesive suction, which arises from the attraction between particles in fine-grained soils, can greatly affect water moving through the soil matrix. The results reveal distinct differences in the permeability coefficients among the three clayey soils. Notably, clayey soil 3 exhibits the highest permeability coefficient, indicating that this soil allows water to pass through more readily under the same cohesive suction. This result suggests that soil 3 has more open pore sizes or lower soil cohesion, which facilitates higher permeability. On the other hand, clayey soil 1 demonstrates a significantly lower permeability coefficient compared to the other two soils when subjected to the same cohesive suction. This lower permeability may be due to a denser pore structure or stronger cohesive forces between particles, which restrict water flow more effectively. These findings show that even within the same soil classification, there can be substantial variations in permeability, which are influenced by cohesive forces.

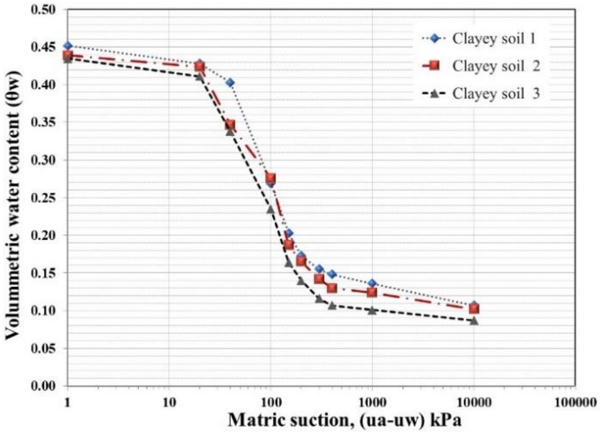


Figure 2. *SWCCs of three clayey soils*

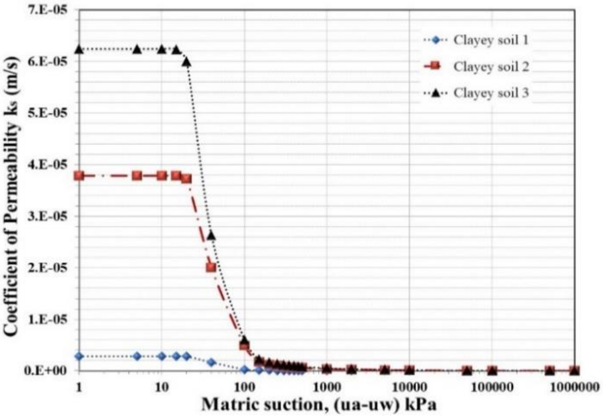


Figure 3. *Permeability coefficients of three clayey soils*

3. Simulation by Geo-slope 2D

In investigation, we utilize the SEEP/W and SLOPE/W software modules within the GeoStudio 2023 geotechnical software suite by GEO-SLOPE to address fundamental problems such as permeability and slope stability calculations. The SLOPE/W software integrates with the SEEP/W module to determine the limit equilibrium slip surface and stability coefficient of slopes using the effective stress and pore water pressure equilibrium method. The simulation steps are conducted as shown in Figure 4.

In the field of geological engineering, ensuring the stability of slopes is extremely important to prevent collapses and accidents. To assess slope stability, the Bishop method, one of the most popular methods in this field, is commonly used [19]. The Factor of Safety (FoS) is used to measure the level of safety of slopes. In this study, FoS is used to evaluate stability. A higher FoS value means it provides greater safety against collapse and accident risks. This also implies that slopes are more resilient under various conditions. According to the standard *TCVN4054-2005* [20], if the value FoS is greater than 1.25, the slope is considered safe, and there is no landslide risk.

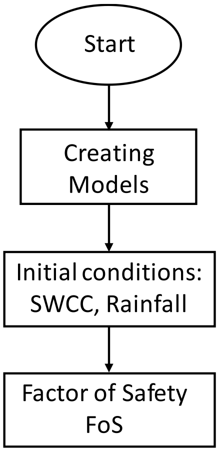
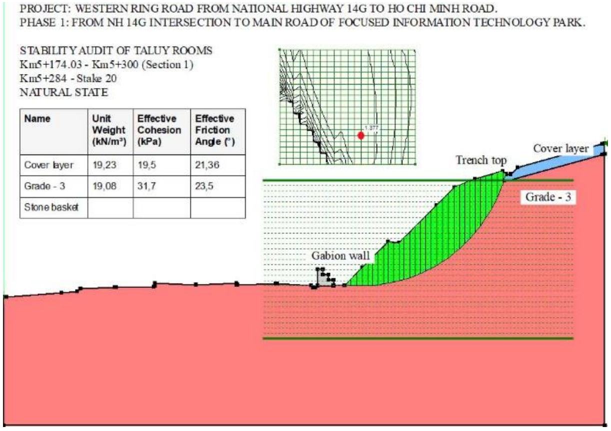


Figure 4. *Steps in simulation by Geo-Slope 2D*

4. Results and discussions

4.1. Consideration of safety of earthen slope

Figure 5 shows the result of a simulation assessing the stability coefficient of the slope at the location of clayey soil 1 under natural, unsaturated conditions. The simulation reveals that the slope at this site achieves a Factor of Safety (FoS) of 1.377, which is generally considered to provide a reasonable level of safety under dry or near-dry conditions. This suggests that the slope is stable under typical conditions, with a sufficient value FoS to prevent failure.


PROJECT: WESTERN RING ROAD FROM NATIONAL HIGHWAY 14G TO HO CHI MINH ROAD.
PHASE 1: FROM NH 14G INTERSECTION TO MAIN ROAD OF FOCUSED INFORMATION TECHNOLOGY PARK.

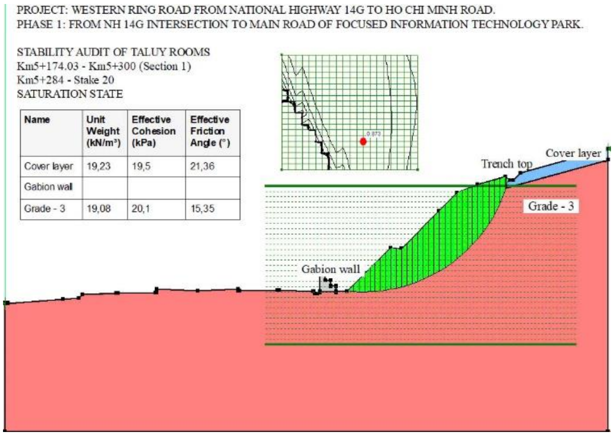
STABILITY AUDIT OF TALUY ROOMS
Km5+174.03 - Km5+300 (Section 1)
Km5+284 - Stake 20
NATURAL STATE

Name	Unit Weight (kN/m³)	Effective Cohesion (kPa)	Effective Friction Angle (°)
Cover layer	19,23	19,5	21,36
Grade - 3	19,08	31,7	23,5
Stone basket			

Figure 5. *FoS under natural soil conditions*

Despite this initial assessment, real-world observations indicate that this slope at Route 14G frequently experiences severe instability during the rainy season. This period is characterized by heavy rainfall, with average precipitation levels ranging from 120 mm to 400 mm. Such heavy rain significantly alters the soil's moisture content, often leading to saturation. This change in conditions is critical because it affects the soil's internal structure and the interactions between soil particles, which can dramatically reduce slope stability.

To further understand this instability, we conducted additional simulations to evaluate the slope's stability under saturated soil conditions. The results of these simulations, as shown in Figure 6, show a significant decrease in the FoS, dropping to 0.873 when the soil is fully saturated. This value FoS is well below the safe threshold, indicating a high likelihood of slope failure under this condition.


PROJECT: WESTERN RING ROAD FROM NATIONAL HIGHWAY 14G TO HO CHI MINH ROAD.
PHASE 1: FROM NH 14G INTERSECTION TO MAIN ROAD OF FOCUSED INFORMATION TECHNOLOGY PARK.

STABILITY AUDIT OF TALUY ROOMS
Km5+174.03 - Km5+300 (Section 1)
Km5+284 - Stake 20
SATURATION STATE

Name	Unit Weight (kN/m³)	Effective Cohesion (kPa)	Effective Friction Angle (°)
Cover layer	19,23	19,5	21,36
Gabion wall			
Grade - 3	19,08	20,1	15,35

Figure 6. *FoS under saturated soil conditions*

Given this result, it is evident that slope instability at this location is a significant concern, particularly during the rainy season. To address this issue, it is crucial to conduct a more detailed analysis of the impact of rainfall on slope stability. This includes investigating how varied rainfall influences the subsequent changes in the FoS. Such an analysis is discussed in the next section.

4.2. Effect of rainfall on slope stability

For this research, the effect of rainfall is modeled in Figure 7. The boundary conditions are AC and BD with total flux Q = 0 m^3/s, AB with total head H = 0 m, and CD with the rain infiltration q (m/s). The soil properties are presented in Table 1 and Figures 2 and 3.

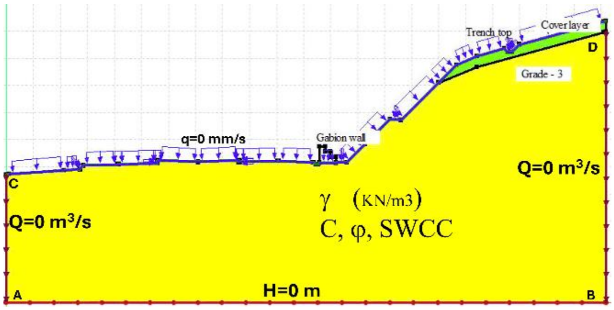


Figure 7. *Geoslope model for rainfall effective on the slope*

The SWCC and Permeability model in Geoslope is used in the results in Figure 2 and Figure 3. For a more thorough analysis and assessment of rainfall impact on slope stability, parameters regarding the SWCC and permeability function (see Figure 8a and 8b) of three different clayey soils at various locations along Route 14G are utilized. These parameters are combined with the average daily rainfall data for Danang City in 2021 (see Table 2).

Figure 9 illustrates the values FoS for three clayey soils, each corresponding to different SWCCs, under varying rainfall conditions. Initially, under dry conditions without the influence of rainfall, the values FoS for all three clayey soils are relatively similar, each approximately 1.377. This initial similarity suggests that slopes are generally stable without external factors such as rainfall or SWCCs. However, the presence of rainfall significantly alters this stability. As rainfall is considered, the FoS values for three clayey soils begin to decrease, and this descent accelerates as the rainfall increases. This finding is crucial because it highlights the impact of rainfall on slope stability, showing that even soils with similar initial values FoS can exhibit markedly different behaviors when exposed to moisture.

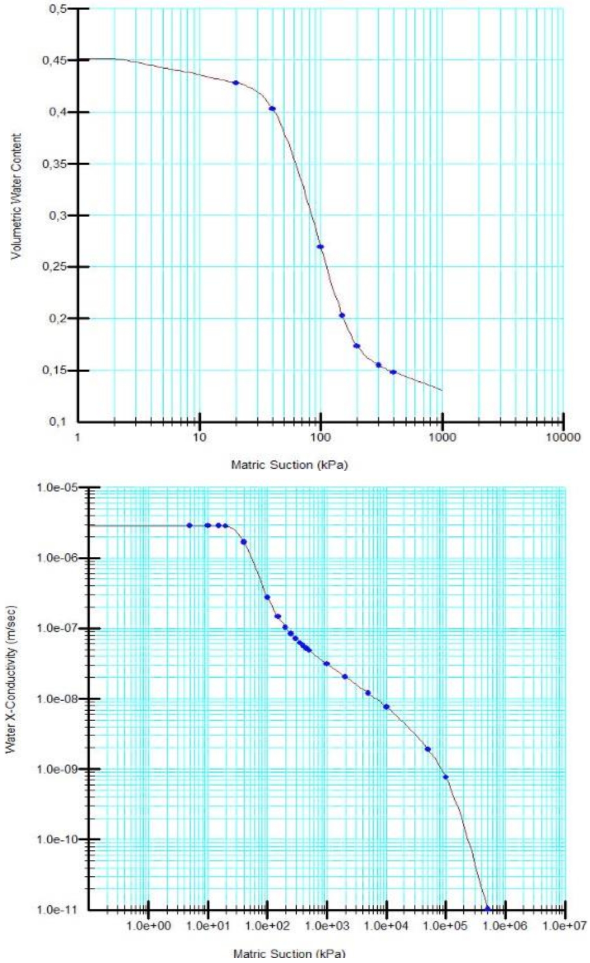


Figure 8. *(a) SWCC and (b) permeability function*

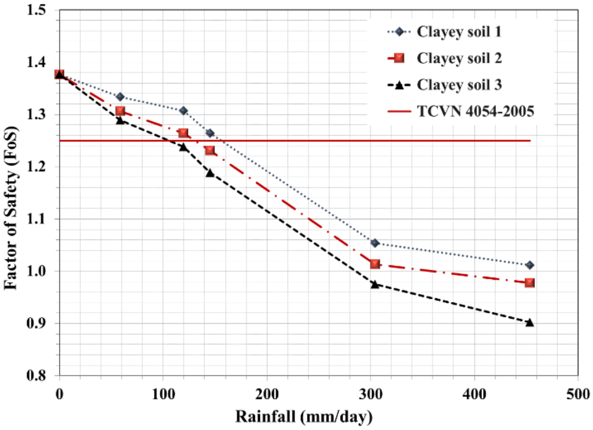


Figure 9. *Values FoS under different rainfall*

Table 2. *Month average rainfall parameters in Danang – 2021 [21]*

Month	7	8	10	11	12
Rainfall (mm/day)	58.6	120	473	304	145

An interesting observation is the identification of specific rainfall thresholds that trigger slope instability. For clayey soil 3, slope instability occurs at 100 mm/day rainfall. Clayey soil 2 reaches instability at 130 mm/day rainfall. Clayey soil 1, the most permeability resistant among the three soils, becomes unstable at 160 mm/day rainfall. These results indicate that clayey soil 3 is the most vulnerable to rainfall-induced instability, whereas clayey soil 1 exhibits greater resistance.

Slope instability can occur at relatively low rainfall before saturation for three soils. This result emphasizes the significant influence of the SWCC on slope stability under rainfall impact, particularly becoming more pronounced with higher rainfall. Additionally, slopes experience instability even with relatively low rainfall. This suggests that instability does not occur at saturation, highlighting the complex interplay between soil properties and rainfall.

To further investigate this relationship, Figure 10 presents the values FoS for the three clayey soils at a specific rainfall of 120 mm/day. The results show a noticeable decrease in FoS, with values ranging from 1.238 for clayey soil 3 to 1.307 for clayey soil 1. This gradual decrease in FoS highlights the varying sensitivity of the different soils at the same rainfall. Clayey soil 3, in particular, is shown to be highly sensitive to rainfall, which can be attributed to its lower cohesive strength. As cohesive strength decreases, the soil's shear strength also diminishes.

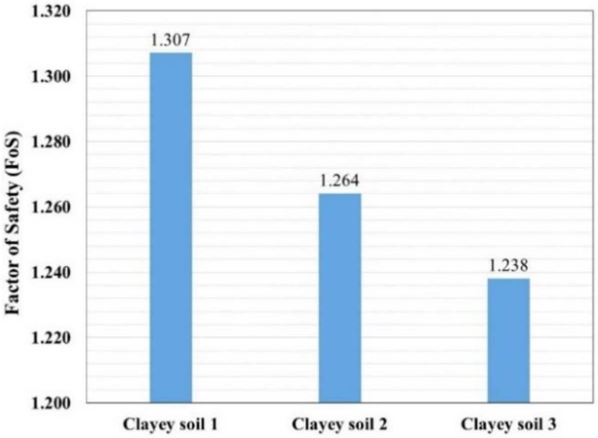


Figure 10. *Influence of SWCC and k_{sz} on FoS at rainfall 120 mm/day*

This result underscores that despite being of the same clayey soil, different SWCCs lead to varying slope stability under the influence of rainfall. This highlights the importance of considering the specific characteristics of soil properties, such as SWCC, in evaluating slope stability under changing environmental conditions. Moreover, it emphasizes the need for appropriate mitigation measures to address the unique challenges posed by different soils and their responses to rainfall.

5. Conclusion

Geo-Slope 2D allows us to incorporate the specific characteristics of the soils and the historical rainfall patterns in the region into our analysis, ensuring a slope stability evaluation based on FoS. By considering soil properties, such as SWCCs, permeability coefficients, and the actual rainfall data, we aim to gain deeper insights into rainfall's influence on the stability of the slopes.

Our findings reveal several key insights into the rainfall effect driving slope instability. Firstly, the analysis shows that soil properties, particularly the SWCCs, play a significant role in determining how slopes respond to varying levels of rainfall. Soil with a higher permeability coefficient, like clayey soil 3, is more prone to rapid decreases in the FoS as rainfall increases, leading to an earlier onset of instability compared to soils with a lower permeability coefficient. This indicates that even slight increases in rainfall can impact slopes composed of such soils, making them more vulnerable to failure.

Secondly, by combining historical rainfall data, it is possible to identify critical rainfall thresholds that correspond to slope instability. These thresholds provide a valuable reference for predicting future slope behavior, as they highlight the specific conditions under which slopes are likely to become unstable.

Moreover, the result emphasizes that slope instability does not only occur when soils reach full saturation. Instead, the findings suggest that the interplay between moisture content and soil properties can lead to instability at lower rainfall well before saturation. This insight challenges the conventional assumption that saturation is the primary driver of slope failure. It suggests that other factors, such as changes in soil suction and shear strength, may also be considered.

Soils with SWCCs having high saturation moisture content (θ_w) and large Air-Entry Value (AEV) result in a higher Factor of Safety.

Finally, these findings provide a deeper understanding of the underlying factors affecting slope instability and offer valuable information for developing effective mitigation strategies for Route 14G.

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