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Effect of groundwater level on slopes to construct the SWCC curve for unsaturated soil

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Abstract

The occurrence of landslides and rockfalls has been on the rise, leading to unfortunate consequences and instilling anxiety and fear within the population as the rainy season approaches. During this time, the soil experiences a significant influx of water, causing the water level to rise and the transition from unsaturated to saturated soil. As a result, the shear strength of the soil decreases, leading to gradual slope instability. While the parameters of unsaturated soil resemble those of saturated soil, the inclusion of a SWCC curve is necessary. This study aims to examine the impact of groundwater levels on slope stability by considering the SWCC curve of the soil using the finite element method. The findings reveal that with an increasing groundwater level, the safety factor remains constant when the slope is assumed to be fully saturated. However, when the slope is evaluated with both fully saturated and unsaturated components using the SWCC, the safety factor declines significantly from 1.82 to 0.393. Similarly, according to the Fredlund-Xing method, the safety factor decreases from 1.754 to 0.393. Regardless of the method used, the safety factor consistently decreases as the groundwater level rises, eventually converging to the same value when the groundwater level reaches the ground surface.

Keywords : SWCC; Slopes; Saturated soil; Unsaturated soil; GeoSlope

1. Introduction

Vietnam, situated in the tropical monsoon region, experiences abundant rainfall and high levels of humidity. The country boasts diverse natural landscapes, with three-quarters of its territory covered by hills and mountains, particularly in the low-lying areas. However, despite significant economic and social development, Vietnam faces growing challenges such as soil erosion in mountainous regions and landslides along riverbanks and coastal areas. These phenomena have increasingly affected the lives and property of both the state and its citizens, as well as the infrastructure and cultural assets, thereby hindering the progress of economic and social development [1-3].

Landslides are often triggered by extended rainy seasons and heavy rainfall, resulting in severe destruction. The infiltration of rainwater into potential slopes and natural slopes raises the groundwater level, exerting additional pressure on void areas. Consequently, the adhesion and anti-shear properties of the soil, as well as slope stability, are compromised. To accurately assess the impact on the natural stability of slopes and potential slopes, it is essential to consider the increased groundwater level in the analysis [4-5].

While saturated soil mechanics theories have been extensively studied, there is a lack of research on the mechanical properties of unsaturated soils in Vietnam. Understanding the influence of shear strength on slope stability in unsaturated soils remains an important area of investigation. Various properties, including permeability, deformation, shear strength, and slope stability, exhibit variations depending on the degree of saturation, moisture content, and

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suction in unsaturated soils. Moreover, the unique origins, conditions, and climate in Vietnam contribute to distinct physical and mechanical properties, especially in unsaturated soils. Relying solely on data from other countries cannot accurately determine the values for Vietnam's soils. Therefore, the establishment of laboratory equipment to determine unsaturated soil properties is crucial for Vietnam to align with advanced countries worldwide. The laboratory provides various methods to create different unsaturated soil environments, one of which involves altering the saturation degree by modifying the volume of water within predetermined void spaces [5-7].

The SWCC curve serves as a vital tool to calculate the properties of unsaturated soils. However, it is crucial to consider the influence of groundwater on slope stability when developing the SWCC curve for accurate analysis. The rise in groundwater level affects the degree of saturation, moisture content, and suction within the unsaturated soils, subsequently impacting their permeability, deformation, shear strength, and overall slope stability [8].

In order to understand and assess the impact of groundwater on slope stability, it is necessary to conduct further research. The study aims to investigate how the groundwater level influences the behavior and stability of unsaturated soils in Vietnam. By analyzing the data and observations, the researchers aim to enhance our understanding of the mechanical properties of unsaturated soils and develop improved methodologies for slope stability analysis.

1.1. Research Overview

Slope stability, groundwater, and the soil-water characteristic curve (SWCC) are important factors to consider in geotechnical analysis. Slopes, whether natural or man-made, tend to become more stable by reducing their steepness and considering both internal and external forces. The shape of the sliding surface on unstable slopes can vary, with a rotating circular cylinder often assumed for simplicity. However, complex sliding surfaces can arise in the presence of hard rock layers or weak soil layers [7-8].

Groundwater, also known as subterranean water, exists below the Earth's surface in soil voids and rock fractures. Groundwater aquifers store usable water, and the water table represents the level at which void spaces are fully saturated. Groundwater is replenished by precipitation and finds its discharge point at rivers and streams. When a river is fed by groundwater, it is known as a gaining stream.

In the context of soil behavior, both saturated and unsaturated soils are influenced by climate conditions. Saturated soil, found below the water table, has a positive pore water pressure. On the other hand, unsaturated soil, located above the water table, exhibits negative pore water pressure due to the presence of air in the pores. Rainfall and evaporation play a significant role in altering the distribution of pore water pressure, affecting the shear strength and stability of slopes [9].

To study and understand the behavior of unsaturated soil, the soil-water characteristic curve (SWCC) is determined through laboratory experiments. The SWCC describes the relationship between suction force and moisture content in unsaturated soil. The pressure plate test method, utilizing equipment such as the Tempe pressure chamber and volume-controlled pressure plate extractor, is commonly used to establish the SWCC. These experiments involve applying varying suction forces to soil samples and measuring the corresponding moisture content. By comprehending the SWCC, engineers can better assess the behavior and stability of unsaturated soil [10].

2. Material and method

Currently, the evaluation of slope stability often relies on the safety factor as a key indicator. Various theoretical calculation methods, such as the limit equilibrium method, limit analysis method, and numerical analysis method, have been developed and applied to assess the stability of both natural and man-made slopes [10-11].

Among these methods, the widely used approach in practice is the limit equilibrium analysis with column division. This method is based on the principle of statics, focusing on the equilibrium of forces and moments, while disregarding soil displacement. The calculation process assumes that the sliding surface of the slope can be approximated as a circular cylinder, making it practical and relatively straightforward for computations [12].

The stability of a slope is quantitatively evaluated using a stability factor, denoted as Fs. This factor represents the ratio between the total moment of resisting forces, Mg (including cohesion and friction of the soil), and the total moment of driving forces, Mt (consisting of external loads, weight of the sliding block, water pressure, seepage pressure, and other relevant factors) [13]:

$$F_s = \frac{M_g}{M_t} \geq [F_s] \quad \text{................(1)}$$

Where: $[F_s]$ is permissible anti-sliding stability factor, dependent on the rank of the construction, as specified by regulations.

In slope stability analysis that incorporates unsaturated soil conditions, consideration of negative pore water pressure becomes crucial. Various methods can be employed to account for this, such as the "total suction" method. This approach introduces tensile forces into the soil cohesion, allowing for the derivation of equations that incorporate both positive and negative pore water pressure or the nonlinear relationship between shear strength and suction force.

In the "total suction" method, the soil cohesion, denoted as c, is recognized to increase as the suction force rises. The extent of this increase is dependent on the magnitude of the suction force. By incorporating this relationship, the stability factor equations can capture the effects of both the soil's cohesive strength and the influence of suction forces. [i.e., $(u_a - u_w)tg\phi^b$] at different angles of ϕ^b [14].

We already know the equation of saturated soil shear strength. It can be written as follows:

$$\tau_{f_f} = c + (\sigma_f - u_w)_f . tan\, \phi' \quad \text{........................(2)}$$

In Which:

Total suction force.

$$c = c' + (u_a - u_w)_f . tan\, \phi^b \text{..................(3)}$$

Therefore, unsaturated soil is considered to have a total suction force, which includes effective cohesion and suction force [2].

$$\tau_{f_f} = c' + (u_a - u_w)_f . tan\, \phi^b + (\sigma_f - u_w)_f . tan\, \phi' \text{..........(4)}$$

Or

$$\tau_{f_f} = c' + (\sigma_f - u_w)_f . tan\, \phi' + (u_a - u_w)_f . tan\, \phi^b \text{...........(5)}$$

This is also the groundwater equation recommended by Fredlund et al. (1978) to use in construction.

The Equation for Calculating Stability Factor Using Moment Equilibrium

For saturated soil [2].:

$$F^m{}_s = \frac{\sum[c'\beta R + (N - u_w\beta) R\, tan\, \phi']}{\sum \mathrm{Wx} - \sum Nf - \sum kW.e \pm [D.d] \pm A.a} \text{............(6)}$$

For unsaturated soil [4,5] :

$$F^m{}_s = \frac{\sum \left[c'\beta R + \left\{ N - u_w \beta \frac{\tan\phi^b}{\tan\phi'} - u_a \beta \left(1 - \frac{\tan\phi^b}{\tan\phi'} \right) \right\} R \tan\phi' \right]}{\sum \mathrm{Wx} - \sum Nf + A.a} \text{...........(7)}$$

Where:
F_s - stability factor;
R - radius of the slip surface;
N - total vertical forces acting on the base of the soil column;
W - total weight of the soil column calculated with width b and height h;

A - total outside water pressure;
D - concentrated load;
kW - seismic horizontal forces acting at the center of gravity of each soil column;
a - distance from the water pressure A to the moment center;
x - horizontal distance from the center of the soil column to the moment center;
f - distance from the vertical force N to the moment center;
d - perpendicular distance from concentrated load D to the moment center;
e - vertical distance from the center of the soil column to the moment center;
b - thickness of the soil column's base along the slip surface; b - inclined width of the soil column's base;
α - angle between the tangent line through the center of the base of each soil column with the horizontal axis.

The method applied to analyze the stability of dam slope in the paper is the limit equilibrium method using effective stress and pore water pressure to determine the stability factor of the slope.

3. Results

Constructing the SWCC curve

The soil volumetric moisture content calculated by equation

$$\theta_w = \frac{V_w}{V}(100) \text{.........}(8)$$

Where:
V_w - the volume of water in the soil sample when the sample weight reaches the stability value corresponding to a specified suction value, in cm^3.
V - total sample volume, equal to 60 cm^3.

The experimental results of determining the soil-water characteristic curve are presented in Tables 1 and Figure 1, representing the soil-water characteristic curves - SWCC. Initially, the soil samples were saturated, and the suction was 0 kN/m2, then the suction was increased by increasing the air pressure and measuring the volume of water released from the sample. This measurement was carried out by weighing the sample after each pressure increase and holding it for about 24 hours. The amount of water released is equal to the difference in weight between two weighings.

Table 1 The result of the experiment determines the SWCC curve

No.	**Adhesive force(ua-uw)**	**Ring knife weight + sample**	**Volume of water in sample**	**Volumetric humidity**
	(kN/m2)	(g)	(cm^3)	
1	0	152.300	17.647	0.294
2	10	151.520	16.867	0.281
3	20	149.735	15.082	0.251
4	30	148.420	13.767	0.229
5	50	147.554	12.901	0.215
6	80	147.020	12.367	0.206
7	100	146.610	11.957	0.199
8	200	146.157	11.504	0.192
9	300	145.840	11.187	0.186
10	400	145.701	11.048	0.184

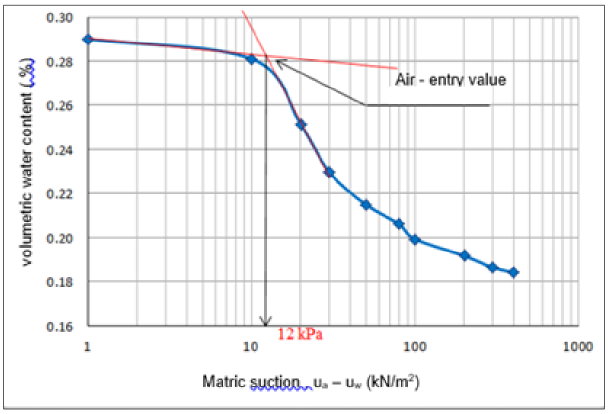

Figure 1 The soil-water characteristic curve (SWCC)

The unsaturated soil air entry value (AEV) of 12kPa represents the suction force necessary for air to permeate through the largest soil pores. The determination of the AEV value for a given sample involves the intersection of two tangents on the graph. One tangent is drawn at the beginning of the curve, representing a low suction force that is required initially. The other tangent is drawn at the steepest slope of the Soil-Water Characteristic Curve (SWCC), indicating the point where the soil experiences the most significant reduction in water content due to suction force.

Figure 1 visually illustrates these characteristics. At the initial stage, corresponding to a low suction force, gas is unable to penetrate the largest soil pores, resulting in minimal changes in soil water content and a nearly horizontal SWCC curve. However, when the suction force in the sample exceeds the air entry value of 12kPa, gas begins to enter the largest soil pores, causing water to escape from the soil. This leads to a rapid decrease in soil water content as the suction force increases. Figure 1 clearly demonstrates the substantial decrease in soil water content once the suction force surpasses the air entry value. Afterward, as the suction force continues to increase, the reduction in soil water content becomes relatively small, resulting in a nearly horizontal segment on the SWCC curve

Calculation of slope stability coefficient in natural conditions when considering unsaturated soil: *To explore the variations in the slope stability coefficient of unsaturated soil, our investigation begins by considering the groundwater table at the time of the survey and the parameters associated with saturated soil. Subsequently, we introduce the parameters specific to unsaturated soil*.

To calculate the slope stability using the GeoSlope software, we employ integrated analysis methods available within the software. This involves adjusting the input parameters to reflect the transition from saturated to unsaturated soil conditions. Initially, the parameters are adopted from those of saturated soil, and then additional components related to unsaturated soil are incorporated. By distinguishing between unsaturated and saturated soil, different scenarios are modeled, resulting in distinct slope stability coefficients.

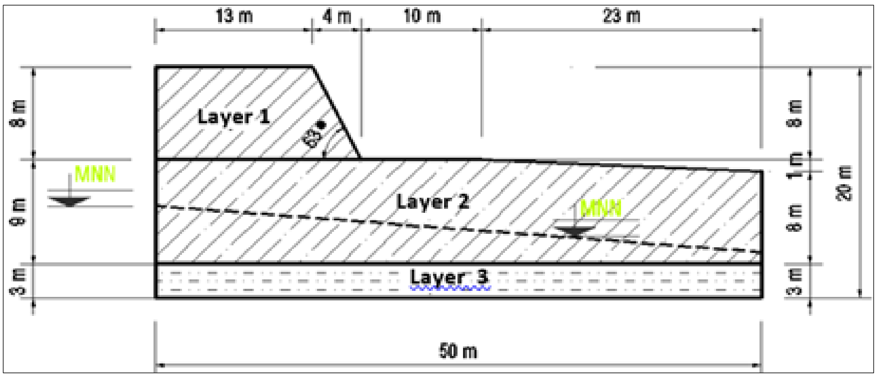

Figure 2 Soil layers of slopes

Throughout these analysis methods, we maintain the geometric structure, sliding center grid, and sliding face grid of the sloping roof. The modifications are solely focused on altering the soil parameters to accurately represent the transition from saturated to unsaturated soil conditions.

Characteristics and properties of slopes. : The sloping roof used for calculations is a natural sloping roof consisting of three geological layers. The calculated cross-section of the natural sloping roof (Figure 2) includes three layers

Table 2 Soil parameters used in the model

Soil layer	Depth (m)	Soil density (kN/m^3)	Angle of interior friction (độ)	Soil cohesive strength (kN/m^2)
Layer 1	0 – 8	18.11	$27^{0}55$	33.7
Layer 2	8 - 17	19.6	$14^{0}05$	25.3
Layer 3	17 - ……	20.2	$14^{0}05$	33.1

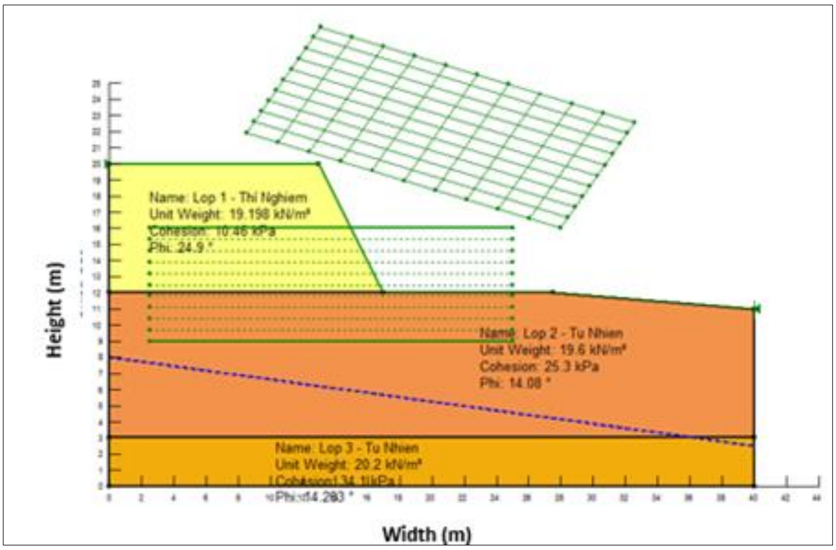

Figure 3 Computational model in Geo – Slope

The sliding center grid and sliding face grid of the sloping roof are depicted in Figure 3, and the equipotential lines in the sloping roof are divided according to Figure 4.

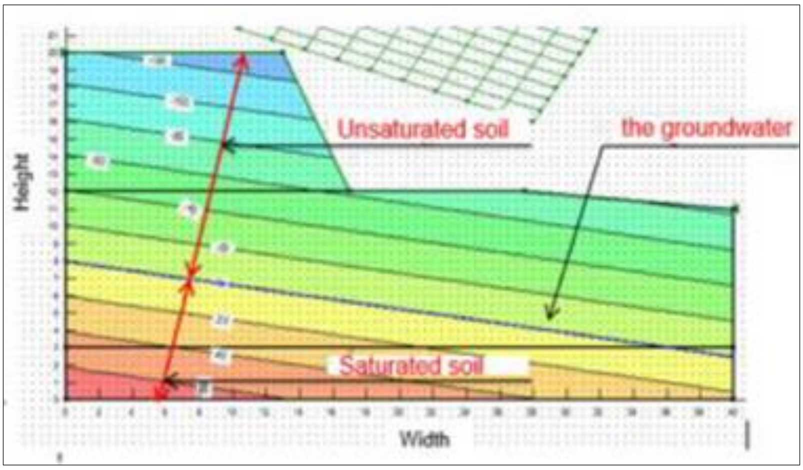

Figure 4 Isometric line model for unsaturated soil and saturated soil in Geo - Slope

When calculating the stability factor using the GeoSlope software, the parameters are maintained constant throughout the analysis. The process involves utilizing the soil testing results obtained at different saturation levels and inputting them into the SLOPE/W module of the GeoSlope software.The software employs a circular sliding surface model to calculate the slope factor. By providing the relevant parameters from the soil testing results, such as soil cohesion, friction angle, unit weight, and pore water pressure at different saturation levels, the software performs the necessary computations to determine the slope stability factor. By keeping the parameters constant and utilizing the circular sliding surface model, the GeoSlope software enables accurate analysis and assessment of slope stability under various saturation conditions..

4. Discussion

Similar to the analysis method above, the area above the groundwater level is unsaturated soil, and below it is saturated soil. The equipotential lines in this case are also divided as shown in Figure 5. However, for the unsaturated soil area, we use the soil parameters of layer 1 with negative capillary forces based on the soil-water characteristic curve testing results input into the model.

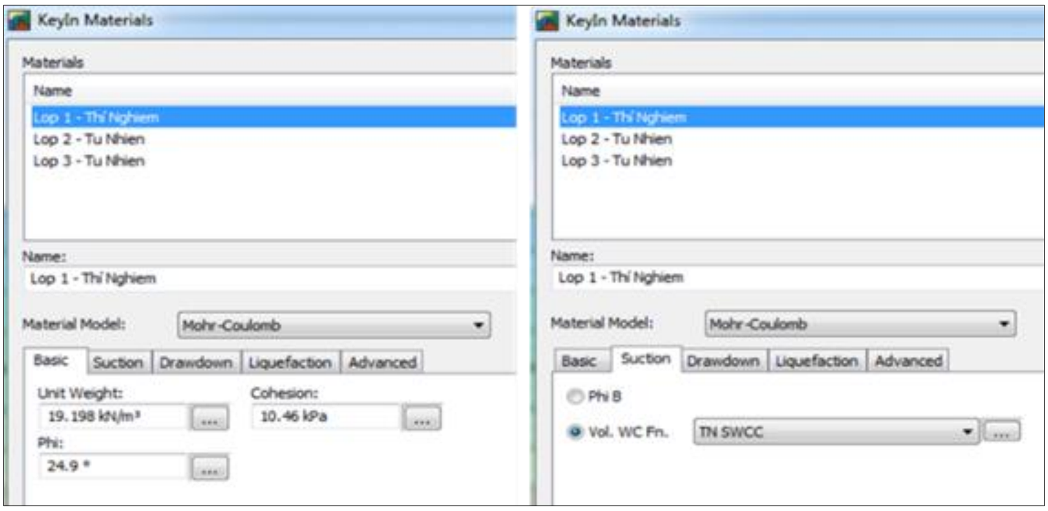

Figure 5 Soil layer 1, SWCC use case

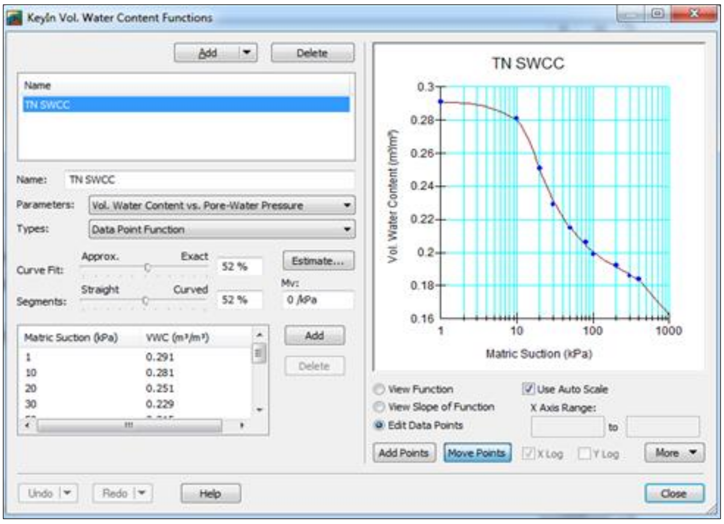

Figure 6 SWCC curve calculated by Geo - Slope

In Figure 6, we see that when we input the testing parameters of the SWCC curve, Geo-Slope also graph the SWCC curve as shown in the result of Figure 6, and Geo-Slope uses this graph to calculate the parameters of unsaturated soil in areas where negative capillary forces vary. The results of calculations in real-world conditions shown in figure below.

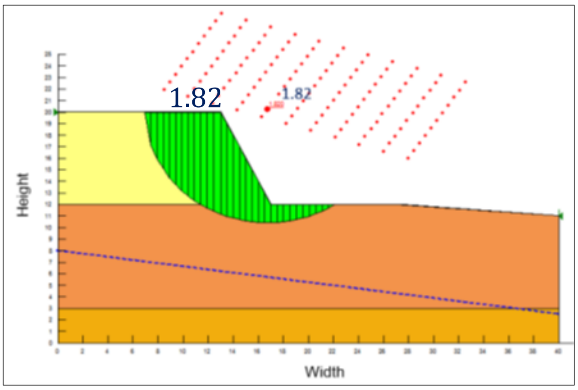

Figure 7 Results of slope stability using SWCC curve

The effect of groundwater saturation changes on the stability of sloping roofs when using the swcc curve. To examine the effect of groundwater level on the stability factor of the sloping roof, we change the groundwater level in the model in the Geo-Slope software at different depths and calculate the stability factor. To do this, we take the groundwater level (12m below ground level) as a reference point, and increase the groundwater level by 1m increments until the groundwater level reaches the surface.

The software automatically divides the equipotential lines for the saturated and unsaturated soil areas based on the groundwater level. As shown in the figures, as the groundwater level increases from below to near the surface, the area of saturated soil increases while the area of unsaturated soil decreases.

The results of the safety factor when the groundwater level increases by 1m increment and is analyzed by 3 methods: the SWCC method:

Table 3 Slope stability coefficient when groundwater level changes in SWCC

No.	Method	Value
1	Method of groundwater level according to survey records	1.820
2	Assume that the groundwater level increases by 1m	1.751
3	Assume that the groundwater level increases by 2m	1.647
4	Assume that the groundwater level increases by 3m	1.543
5	Assume that the groundwater level increases by 4m	1.438
6	Assume that the groundwater level increases by 5m	1.332
7	Assume that the groundwater level increases by 6m	1.215
8	Assume that the groundwater level increases by 7m	1.095
9	Assume that the groundwater level increases by 8m	0.97
10	Assume that the groundwater level increases by 9m	0.849
11	Assume that the groundwater level increases by 10m	0.737
12	Assume that the groundwater level increases by 11m	0.628
13	Assume that the groundwater level increases by 12m	0.543
14	Assume groundwater level at ground level	0.393

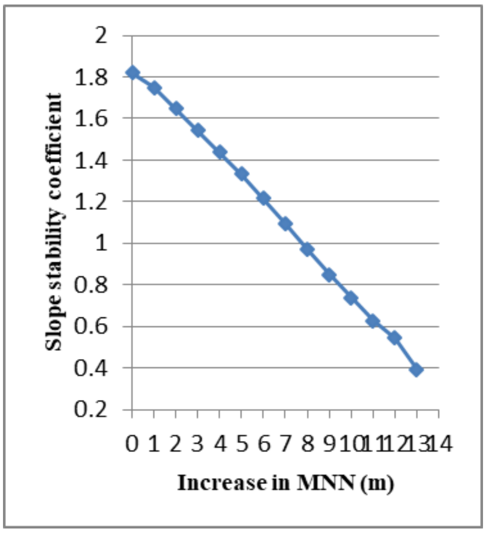

Figure 8 Slope stability coefficient when groundwater level changes according to the SWCC method

Calculation of Stability coefficient of Slope When groundwater level changes with saturated and unsaturated soil. The stability analysis of a sloping roof can be calculated using GeoSlope software, which incorporates various analysis methods that can be adjusted by changing input parameters. The initial parameters are based on saturated soil conditions, and additional parameters for unsaturated soil conditions, such as the Soil Water Characteristic Curve (SWCC), are also included. The updated parameters determine whether the soil is saturated or unsaturated, and ultimately contribute to the stability coefficients of the sloping roof in various scenarios. By using GeoSlope software, three analysis methods can be applied to the sloping roof.

- Method 1: Analysis with Saturated Soil
- Method 2: Analysis with Unsaturated Soil Using Soil-Water Characteristic Curve (SWCC)
- Method 3: Analysis with Unsaturated Soil Using Parameters (a,m,n) According to Fredlund-Xing.

As groundwater levels rise above the natural ground surface, the unsaturated soil zone decreases while the saturated soil zone increases. The results for the three methods using Geo-Slope software are shown in the following table and Figure 8 and Figure 9.

Table 4 Stability coefficients of sloping ground when groundwater level increases using three methods

No.	**Method**	**Calculated according to SWCC**	**Calculated according to Fredlund - Xing**	**Calculated according to saturated Soil**
1	Method of groundwater level according to survey records	1.820	1.754	0.9
2	Assume that the groundwater level increases by 1m	1.751	1.668	0.9
3	Assume that the groundwater level increases by 2m	1.647	1.581	0.9
4	Assume that the groundwater level increases by 3m	1.543	1.493	0.9
5	Assume that the groundwater level increases by 4m	1.438	1.403	0.9
6	Assume that the groundwater level increases by 5m	1.332	1.308	0.9
7	Assume that the groundwater level increases by 6m	1.215	1.201	0.9

8	Assume that the groundwater level increases by 7m	1.095	1.086	0.893
9	Assume that the groundwater level increases by 8m	0.970	0.965	0.843
10	Assume that the groundwater level increases by 9m	0.849	0.847	0.776
11	Assume that the groundwater level increases by 10m	0.737	0.748	0.699
12	Assume that the groundwater level increases by 11m	0.628	0.637	0.618
13	Assume that the groundwater level increases by 12m	0.543	0.548	0.539
14	Assume groundwater level at ground level	0.393	0.393	0.393

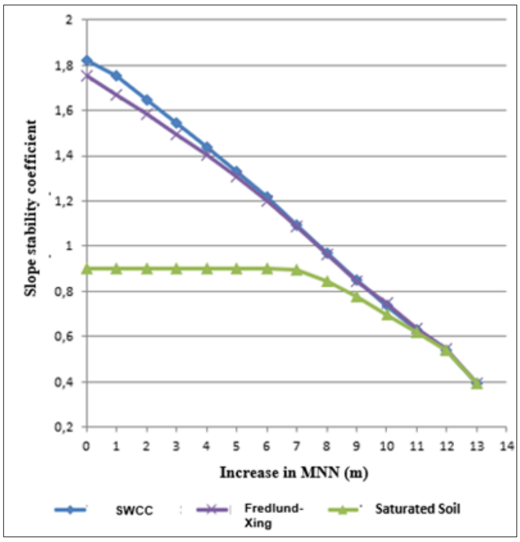

Figure 9 Comparison of stability coefficient when groundwater level changes by 3 methods

As the groundwater level rises close to the ground surface, the stability coefficient decreases, with different methods resulting in varying rates of reduction. When using the SWCC and Fredlund - Xing methods, the stability coefficient decreases almost linearly (in a straight line). On the other hand, when using the saturated soil method, the stability coefficient remains constant when the groundwater level is below a certain depth (greater than 8m) and starts to decrease only when the groundwater level reaches the boundary of the first layer.

When the groundwater level rises close to the ground surface, the stability coefficients of all three methods decrease and converge at one point. This can be explained by the fact that as the groundwater level increases, the area of saturated soil increases while the area of unsaturated soil decreases, until the groundwater level reaches the ground surface and the soil becomes completely saturated. At that point, calculating the stability coefficient using the SWCC or Fredlund - Xing methods is no longer relevant (as there is no unsaturated soil left), and all three methods will yield a stability coefficient value of 0.393.

In the most general case, when considering the transition of soil from saturated to unsaturated states, the stability coefficient values will increase differently when considering groundwater levels at the ground surface (area of fully saturated soil) and when the groundwater level decreases (area of unsaturated soil increases). The stability coefficient value obtained using the SWCC method increases the most, followed by the Fredlund - Xing method, while the saturated soil method yields the smallest increase in stability coefficient. The stability coefficient obtained using the saturated soil metho*d increases non-linearly with depth, until a certain depth where the stability coefficient value becomes constant (a horizontal line).

5. Conclusion

In order to predict the stability of a natural slope using the finite element method in Geo-Slope software, the construction of the Soil-Water Characteristic Curve (SWCC) is essential. It is observed that the natural soil can exist in two states: saturated and unsaturated, each characterized by a distinct SWCC curve. The construction of the SWCC curve is necessary when considering the unsaturated properties of the soil.

The natural slope comprises both saturated and unsaturated soil. When predicting the slope's stability, if we assume the slope is entirely saturated, the stability coefficient is calculated to be 0.9. However, when considering the slope as unsaturated soil and utilizing the SWCC method, the safety factor increases to 1.82. Additionally, when applying the Fredlund-Xing method, the safety factor is determined to be 1.754. Both methods yield safety factors greater than 1, indicating that the slope is considered very safe and stable in its natural state. The existence of the natural slope in reality further supports the understanding that its essence lies in the unsaturated soil condition.

As the groundwater level rises closer to the ground surface, the stability coefficient of the three options decreases linearly and eventually converges at a particular point. When the groundwater level reaches the ground surface, the soil becomes fully saturated. At this stage, calculating the stability coefficient using the SWCC or Fredlund-Xing methods no longer provides meaningful results since there is no unsaturated soil present. In such cases, the stability coefficient of the three options is equal and has a value of 0.393.

The rise of the groundwater level leads to a transition in the soil from an unsaturated state to a saturated state, resulting in a linear decrease in the stability coefficient when using unsaturated parameters. Eventually, when the groundwater level reaches the natural ground surface, the unsaturated soil becomes fully saturated.

Compliance with ethical standards

Acknowledgments

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Disclosure of conflict of interest

All authors contributed positively to the writing of this manuscript and there no conflict of interest as agreed to the content of this research.

Statement of informed consent

Informed consent was obtained from all individuals respondents included in the study.

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