SEBHA UNIVERSITY CONFERENCE PROCEEDINGS, VOL.03 NO. 2 2024
DOI: 10.51984/SUCP.V3I2.3118

وقائع مؤتمرات جامعة سبها
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Analyzing the Effect of Water on Stability of Rocky Slopes and Simulating Collapse: A Case Study of the Debris Slope Parallel to Rujban Mountain Road –NW Libya

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Keywords:
Collapse
Factor Of Safety Resistive Force
Rock Plan Software
Simulation

ABSTRACT

On December 11, 2023, a sudden collapse occurred in a parallel rocky slope adjacent to Rajban Mountain Road, leading to the closure of the road section. This prompted the research idea of simulating the collapse and the influencing conditions to assist in understanding the collapse occurrence. This paper discusses the utilization of practical methods and the 'Rock Plan' software to simulate the stages of slope failure. The analysis of simulation outputs reveals the impact of moisture content on the factor of safety and the relationship between driving forces and resistance. This paper highlights the importance of resistance strength in maintaining slope stability and how it diminished under the influence of rainfall pressure and a 65% increase in moisture content, which resulted in the slope collapse. The results demonstrate the influence of internal cohesion and friction angles on slope stability, identifying them as the primary factors contributing to the collapse. The study emphasizes the importance of using laboratory experiments to determine cohesion values and friction angles. It recommends the necessity of debris removal from water drainage channels and the use of simulation programs to assess the stability of parallel slopes along mountain roads before their construction.

تحليل التأثيرات المائية على استقرار المنحدرات الصخرية ومحاكاة الانهيار دراسة حالة -منحدر الحطام الصخري الموازي للطريق الجبلي الرجبان شمال غرب ليبيا

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الكلمات المفتاحية:
المحاكاة
القوة المقاومة
معامل الأمان
الإنهيار
برنامج روك بلان

الملخص

بتاريخ 2023/12/11 حدث انهيار مفاجئ لمنحدر حطام صخري موازي للطريق الجبلي الرجبان فأدى لإغلاق مسار الطريق فجاءت فكرة البحث بمحاكاة الإنهيار والظروف المؤثرة والمساعدة في حدوث الإنهيار، وتناقش الورقة استخدام الطرق المعملية وبرنامج (Rock Plan) لمحاكاة مراحل انهيار المنحدر، ويكشف تحليل مخرجات المحاكاة عن تأثير المحتوى المائي على عامل الأمان والعلاقة بين قوى الدافعة والمقاومة، وتسلط الورقة الضوء على أهمية قوة المقاومة في الحفاظ على ثبات المنحدر، وكيف تلاشت القوة المقاومة تحت تأثير ضغط مياه الأمطار وارتفاع المحتوى المائي بنسبة 65 % والتي أدت لانهيار المنحدر، وأظهرت النتائج تأثير التماسك الداخلي وزوايا الاحتكاك على ثبات المنحدر وأنها السبب الأبرز في حدوث الإنهيار . و تؤكد الدراسة على أهمية استخدام التجارب المعملية في تحديد قيم التماسك وزوايا الاحتكاك، وتوصي الدراسة بضرورة إزالة الأنقاض من قنوات تصريف المياه واستخدام برامج المحاكاة لتقييم ثبات المنحدرات الموازية للطرق الجبلية قبل الشروع في قطعها.

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Article History: Received 26 April 2024 - Received in revised form 30 july 2024 - Accepted 06 October 2024

1. Introduction

Parallel and adjacent slopes to mountain roads are considered as high risk areas, where the sliding rock debris is prone to sudden and rapid collapses, leading to serious accidents and traffic disruptions [1]. Several factors contribute to the occurrence of slope failures parallel to mountain roads, including the type of soil and rocks, as the stability of slopes is influenced by their characteristics such as porosity and permeability [2]. Rainfall is also a major factor affecting slope stability and hence water-saturated soils are more likely to lead to slope failure [3]. According to reference [4], heavy rainfall increases water pressure in soil and rocks' pores, especially rocks with moderate to high porosity, resulting in reduced cohesion. Reference [5] confirms that water pressure reduces the cohesion of soil and rock components, increasing the likelihood of slope failures. Earthquakes are another factor that causes increased vibrations and changes in soil and rock pressure, leading to the accumulation of stress and subsequent slope failures [6]. Chemical and mechanical weathering processes, as well as weathering factors, contribute significantly to the destabilization of slope components. These factors include wind and rain, especially rill weathering, which penetrates slopes and reduces their stability [7]. Human activities also contribute to increased hazards of slope failures, such as the removal of vegetation cover, which is essential for slope stabilization [8], or altering and blocking natural drainage channels or cutting slopes to extend mountain road paths [9].The interaction of both natural and human factors can affect the stability or collapse of slopes and may be the cause of parallel slope failures along mountain roads [10]. For instance, the Rujban mountain road, as shown in (Figure 1), experienced a collapse of rock debris on 11/12/2023, with the debris extending for a distance of 6 meters (Figure 2) [11].

Fig. 1: A section of Rujban Mountain Road

The collapse. led to road closure, and the debris was removed by road users while burying natural drainage channels.

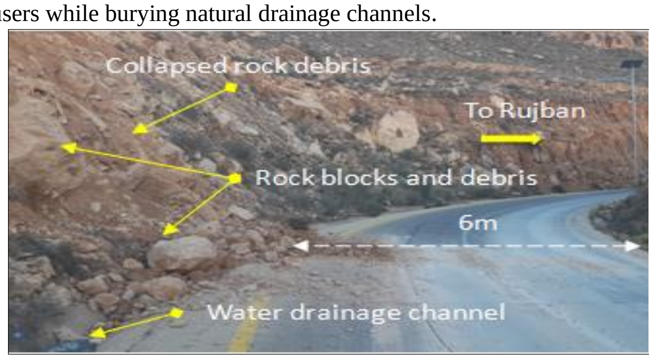

Fig. 2: Rock Debris Collapse at the Study Area Site

Observations also reveal that rock masses on the slope may collapse at any time. This collapse occurred on a rainy day, with recorded rainfall of 80 mm [12].The research problem lies in the sudden collapse that occurred on a slope parallel to the road and the presence of similar rocky slopes that could potentially collapse in the same location or adjacent slopes. Therefore, the research problem raises the following questions: Can the stages of rock debris collapses be simulated at the site? Can the collapse occurs again on adjacent slopes? Finally, is there consistency between the results of laboratory experiments and computer simulations in evaluating slope stability and collapse? To answer these questions, research objectives have been formulated, including determining the values of internal friction angles, evaluating internal cohesion experimentally with varying water content, and simulating the conditions of rock debris slope collapse using the RocPlane Software. According to reference [13] simulating the collapse of parallel slopes along mountain road paths is highly significant in the field of geological engineering and Geotechnical. It contributes to the study and analysis of the threats posed by slope failures, estimating potential risks that may impact road infrastructure and user safety, and mitigating future collapse risks. Simulation of slope collapse relies on the utilization of engineering modeling tools and scientific computing to estimate the forces and stresses affecting the slope, analyze its stability, and assess collapse conditions [14]. To conduct an accurate simulation of slope collapses, it is essential to incorporate the characteristics of the collapsed materials, as well as geological, geomorphological, and slope geometry information to enhance result accuracy [15]. Reference [16] elucidates that the fundamental steps in the process of simulating slope collapse involve determining the properties of slope materials, highlighting external forces at play, estimating internal forces and stresses generated within the slope, and analyzing slope stability based on established engineering criteria to achieve a specified safety factor. The precise simulation of slope collapses empowers engineers and experts to identify high-risk areas and implement suitable preventive measures to minimize risks and ensure user safety. The spatial dimension is confined to a section of Rujban Mountain Road, geographically located north of the city of Rujban, on the northern edge of the mountain., The study area lies between the latitudes N31°59'59"and N31°59'17" and the longitudes E12°06' 07" and E12°08' 07". (Figure 3)

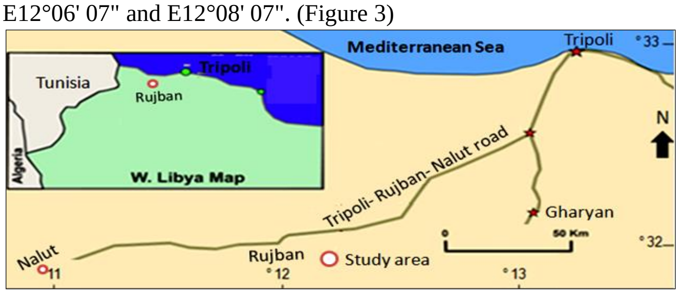

Fig. 3: Location of the study area[16].

1.1- Stratigraphy and Geological Setting of the Area:

The Jebel Rujban highlands and its mountainous road are part of the general stratigraphy within the Nafusa Uplift, which extends from southeastern Tunisia to northwestern Libya, spanning a distance of 400 kilometers [17]. The Formations (Fm) on the parallel and adjacent slopes to the Jebel Rujban mountain road vary, with the most important ones being, from bottom to top, the Kekla Fm overlain by the Sidi As Sid Fm, followed by the Nalut Fm. The stratigraphic sequence concludes with the Tegherneh Fm of the Upper Cretaceous age [18]. It is worth noting that the collapsed slope consists of recent quaternary deposits composed of rock debris, gravel, sand, sandy stone, and sandy loam. These deposits rest on the rocks of the Sidi AS Sid Fm - Ain Tobi Member.

2. Methodology and Results

1.2: Laboratory Study. This stage focused on calculating the values of friction angles, internal cohesion, and water content % for the dry sample and when adding different quantities of water to the dry sample (5mm, 20mm, 50mm, 80mm). The important materials and equipment used are illustrated in (Figure 4).

Fig. 4: Some devices and equipments used in the laboratory

1.1.2: Sample Preparation and Shear Testing Stage.

In the first step a sample was taken from the collapsed debris and immediately placed in a bag approximately eight days after the collapse occurred. A portion of the sample was then taken and put into an Furnace for 24 hours at a temperature of 120°C to dry it out. The moisture content was calculated by weighing the sample before and after drying, the result was recorded. In the second step: a portion of the natural undisturbed sample, without drying, was taken. Tests were conducted on this sample to determine the relationship between the normal stress and the shear stress resulting from the applied load using the Direct Shear Test apparatus, as described in reference [19]. The tests were carried out at a constant loading rate of 0.25 N/cm^2 using a loading frame with an area of 36 cm^2, as shown in (Figure 4). Variable vertical loads (4kg, 8kg, 16kg) were applied, as shown in (Figure 5). The values of the friction angle (φ) and internal cohesion (C) were extracted using a pre-prepared Excel model, as shown in (Figure 6). The results were recorded in Table 1inTable1

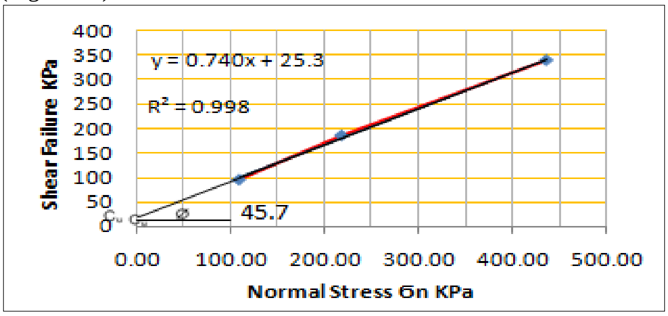

Fig. 5: Variable vertical loading of the sample (4kg, 8kg, 16kg)

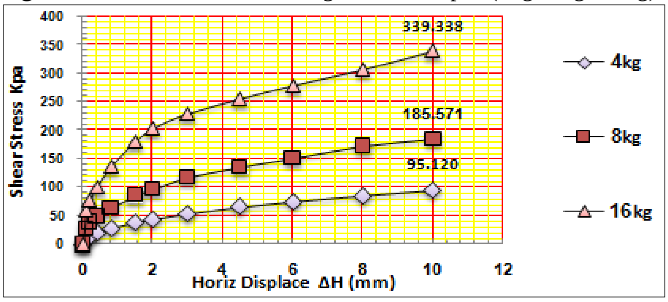

Fig. 6: Relationship between normal and shear stress at 2.8% saturation.

The third step of this stage focused on revisiting the information obtained from the first and second steps. In this step, an additional quantity of 5mm was added to the sample, and values for moisture content, cohesion, friction, and sample density were calculated. The tests were then repeated on the samples after adding water in quantities of 20mm, 50mm, and 80mm. All the data obtained from these tests were recorded in Table 1.The overall objective of these tests was to determine the effect of varying water content on slope failure, considering that rainfall was the triggering factor for the collapse of the slope components.

Table 1: Data and results obtained from the laboratory study.

Water Quantity	Natural.s	5mm	20mm	50mm	80mm
Water Content %	2.8 %	5.9 %	15%	23%	65%
Cohesion	25.3 t/m^2	22.2 t/m^2	11.5 t/m^2	7.3 t/m^2	0 t/m^2
Friction Angle	45.7°	41.6°	24.4°	18.6°	11.4°
Unit Weight	1.2 g/cm^3	11.4 g/cm^3	1.7 g/cm^3	2.1 g/cm^3	2.9 g/cm^3

1.1.2: The Rocplane

At this stage, Used Rocplane software to assess and simulate the stages of slope collapse, considering variations in water quantities represented by cohesion values, friction angles, and density obtained from laboratory studies. Additionally, I incorporate slope engineering data obtained from field measurements. The following description sheds light on the program. Rocplane is a software that aids in analyzing the influential factors on slope stability, such as slope geometry, shear strength, water pressure, and external forces[20]. Rocplane is a software The program empowers users to identify crucial stability factors and evaluate the current level of slope stability according to predefined safety metrics. It enables simulation of the impact of different variables on the stability of rock slopes[21]. Users can modify parameters of slope geometry, shear strength, water pressure, and external forces to determine the most favorable scenario for enhancing slope stability[21]. Moreover, the program excels at analyzing past slope failures, allowing users to investigate and comprehend the causes of such failures. The information derived from the program can be utilized to assess the stability of similar slopes and implement appropriate preventive measures[21].It is worth noting that the program simulates the effect of water pressure on slope components in four stages, depending on the location of water pressure concentration: on the failure plane and on the crack, at the base of tension crack, at the toe of the slope, and at mid-height of the slope[21].. (Figure 7). and the most important data on which the program depends is listed in the table 2.

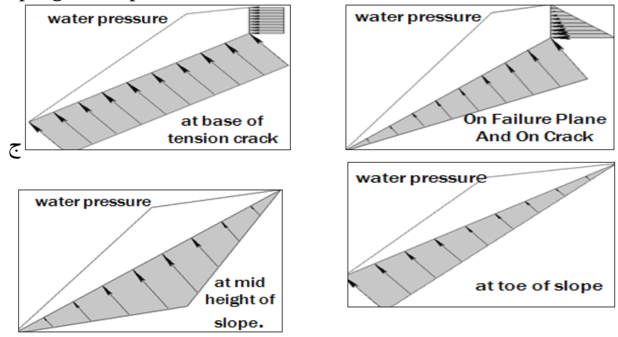

Fig. 7: Water pressure distribution on the failure plane and cracks[21]

Table 2: Input data for rocplane software

water quantity	Natural.s	5mm	20mm	50mm	80mm
Water Content %	2.8 %	5.9 %	15	23%	65%
Slope Angle	70°	70°	70°	70°	70°
Slope Height	8m	8m	8m	8m	8m
Failure angle	38 °	38 °	38 °	38 °	38 °
Bench Width	25m	25m	25m	25m	25m
Seismic Coefficient	0.04	0.04	0.04	0.04	0.04
Discontinuity Angle	90 °	90 °	90 °	90 °	90 °
Distance From Crust	2m	2m	2m	2m	2m
Cohesion	25.3 t/m^2	22.2 t/m^2	11.5 t/m^2	7.3 t/m^2	2.1t/m^2
Friction Angle	45.7 °	41.6°	24.4°	18.6°	5.6°
Unit Weight	1.2 g/cm^3	1.4 g/cm^3	1.7 g/cm^3	2.1 g/cm^3	2.9 *g*/cm^3

The input data listed in Table 2 played a crucial role in obtaining highly significant results that contributed to conducting a Numerical Simulation of the slope failure stages. The results of the simulation have been included in the Table 3.

Table 3: Rocplane software output

water quantity	Natural.s	5mm	20mm	50mm	80mm
Water Content %	2.8 %	5.9 %	15%	23%	65%
Factor Of Safety	9.2	6.5	2.4	1.1	0
Resisting Force	125.8 t/ft	103.4 t/ft	58.4 t/ft	37.6 t/ft	0 t/ft
Driving Force	13.58 t/ft	15.8 t/ft	23.6 t/ft	36.4 t/ft	45.4t/ft
Wedge Weight	20.9 t/ft	24.4 t/ft	29.6 t/ft	36.6 t/ft	0.6 t/ft

3. Discussion of Results.

3.1 Discussion of Laboratory Experiment Results

By analyzing the data in Table 1, we observe changes in the water content ratios, cohesion values, and friction angles with variations in the water quantity under the effect of vertical stress and shear stress applied by the Direct Shear Test apparatus. When increasing the water quantity to 5mm for the dry sample, both cohesion and friction angle values decreased, but the change was minimal compared to the dry sample as shown in (Figure 8). This is due to the dry sample's ability to absorb the 5mm water quantity. The noticeable change occurred when adding 20mm of water, resulting in a significant decrease in internal cohesion to 22.2 t/m² according to Table 1. This decrease is more evident when examining (Figure 8), which coincided with a slight change in the friction angle value. The decrease in cohesion can be attributed to the roughness of the sample, which resists the collapsing process. Further increasing the applied stress on the sample by adding 50mm of water led to the sample reaching a state of suffocation due to the exerted forces and the high water content, which reached 23% according to Table 1. Once the Water content ratio inside the sample reached 56% it completely lost its cohesion, as shown in (Figure 8), and the friction angle decreased to be 11.4°. It is worth noting that the mixed debris porosity played a role in not retaining high water content, resulting in a relative increase in density (Unit Weight) in Table 1 with each change in water quantity. It is important to emphasize here that the changes in friction angles and internal cohesion are influenced by the water content ratio retained by the sample, rather than the added water quantity. The sample did not reach a saturation level of 100% in all cases, yet Failure occurred. Therefore, we can conclude that the cohesion and Failure of the sample are closely related to the water content it contains, which is the crucial factor for slope failure to occur in a laboratory setting.

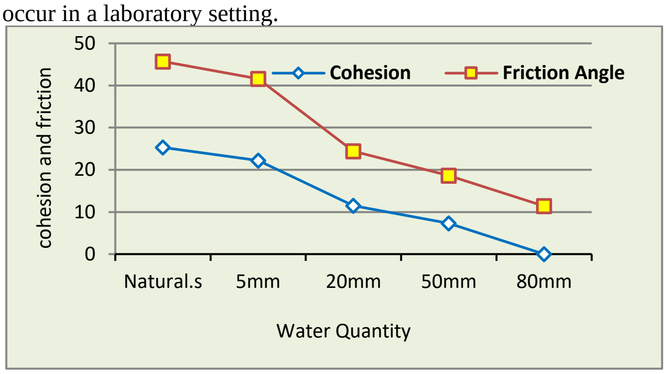

Fig. 8: Relationship between water quantity and cohesion -friction

3.2 Discussion of Results Obtained by Rocplane Software

The utilization of the Rocplane Software allowed for the simulation of slope collapse. Analyzing the outputs presented in Table 3, we observe a significant alteration in the Factor of Safety. Initially, the Factor of Safety reached its peak value of 9.2 when the water content was 2.8 %. However, as the water content ratio reaches to 65%, the Factor of Safety dropped to zero, coinciding with the occurrence of component collapse in Slope (Figure 9).

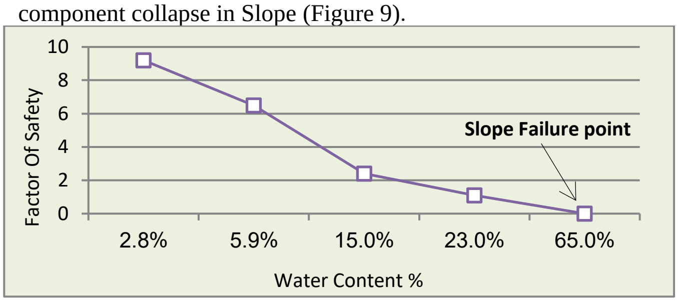

Fig. 9: Relationship between factor of safety and water content %

The observed change in the Factor of Safety values was caused by a strong inverse relationship between the resistance force against collapse and the driving force, as shown in (Figure10). As the driving force increased, the resistance force decreased, leading to a decrease in the safety factor. The relationship between the driving force and the resistance force is influenced by changes in water quantity. When the water quantity increases in the slope, it negatively impacts the resistance force against slope collapse. This is due to several factors, including the increase in weight resulting from the load caused by the higher water content percentage.

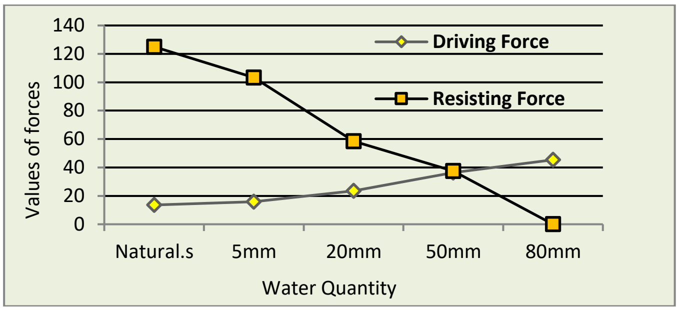

Fig. 10: Relationship between driving and resistance forces

The resistance force played a crucial role in maintaining the stability of the slope. Through the analysis of the data in Table 3, we find that the resistance force in the natural condition of the slope was 125.8 t/ft, which is a substantial force compared to the driving force that triggers collapse, which was 13.58 t/ft. The resistance force remained constant, ensuring the stability of the slope, and there was no significant impact from the water quantity or water content ratio on the collapse (Figure 11).

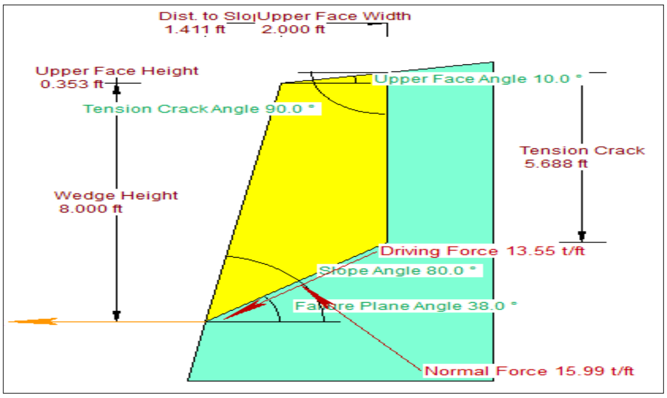

Fig.11: Simulating a natural slope affected by a water content of 2.8%

The actual and influential effect of the driving force began with a value of 23.6 t/ft, coinciding with a decrease in the resisting force by 58.4 t/ft and an increase in Wedge Weight by 29.6 t/ft (Table 3 and Figure 12). We observe the effect of water resulting from rainfall, which acted as a driving force concentrated below the tension crack. Field studies revealed that the tension crack is a discontinuity located at the top of the slope, reaching a depth of up to 5.6 meters. This discontinuity was formed due to water erosion factors, leading to the weakening of the slope, facilitating water infiltration, and increasing the moisture content of the slope components. However, the failure plane was not affected by rain water pressure (Figure 12).

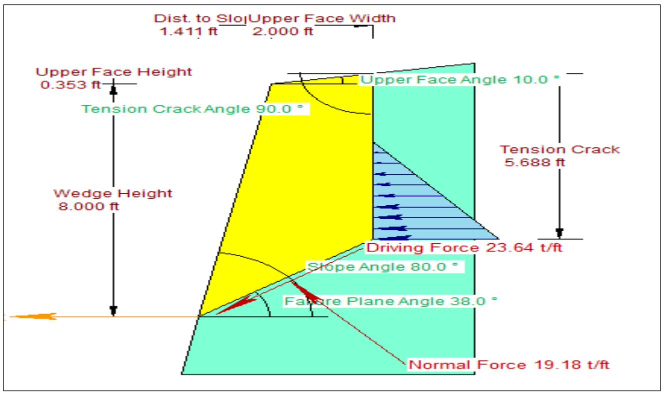

Fig. 12: Simulating a natural slope affected by a water content of 15%

The effect of rainfall water pressure increased when the water quantity reached 50mm, affecting the entire tension crack (Figure 13) This is due to the increased water quantity and water content within the slope components. Simultaneously, the driving force increased by 36.4 t/ft, while the resisting force decreased by 37.6 t/ft, resulting in a decrease in the safety factor to 1.1. As a result, the slope approached the point of failure.

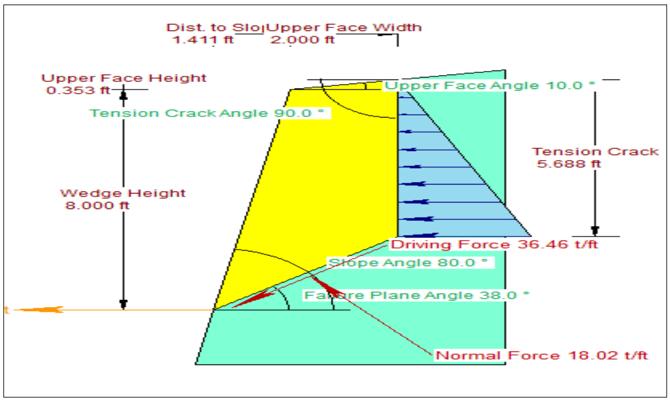

Fig. 13: Simulating a natural slope affected by a water content of 23%

By observing (Figure 15), the clear impact of rainfall water pressure is evident on two locations: the tension crack and the Collapse plane (Figure 14). This leads to an increase in the driving force, reaching a value of 45.4 t/ft, while both the resisting force and cohesion vanish, resulting in a value of 0 t/ft Table 3. The internal cohesion collapse occurs with a value of 2.1 t/m² and a Factor of Safety of 0. It is evident that the collapsed slope was affected by the rainfall water pressure. The effects started to manifest when the slope was exposed to a water quantity of 20mm, continuing through 50mm, and resulting in the collapse of slope components at a water quantity of 80mm. The slope was also influenced by the water content, affecting cohesion, friction angles, and the density of the slope materials.

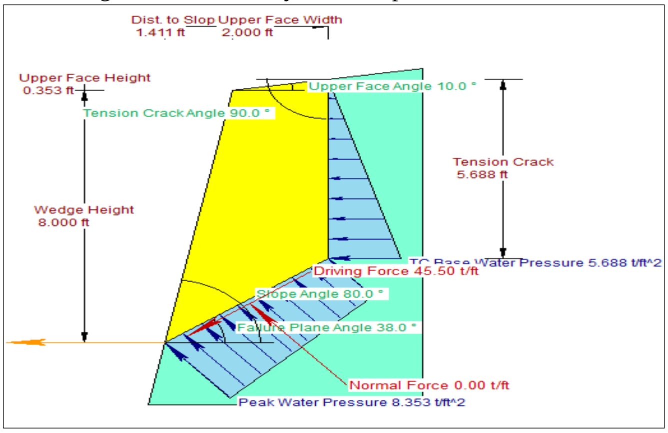

Fig. 14: Simulating a natural slope affected by a water content of 65%

4.Conclusion

The simulation operations conducted on the collapsed slope have revealed the conditions that contributed to the occurrence of slope collapse in the rocky debris slope parallel to the Rujban mountain road. The laboratory experiments played a significant role in determining the values of cohesion, friction, and identifying the actual values of the infiltrated moisture content within the slope components with varying water quantities. It should be noted that the saturation ratio is responsible for the variation in cohesion values and friction angles experimentally. On the other hand, the Rocplane software highlighted that the collapsed slope was affected by two forces. The first one was due to the moisture content, which leads to to changes in cohesion and friction. The second one resulted from the pressure of water from rainfall, causing the slope to collapse at a water level of 80mm, the dissipation of resisting force, and the rise of driving force. It is worth mentioning that the results of this study can be relied upon to issue guidelines for slopes with similar rock characteristics, provided that the slope engineering values align with the failed slope's engineering values. Finally, the study recommends the necessity of removing the collapsed debris that has settled in the water drainage channels, with an emphasis on removing the rock blocks located within the Parallel slopes, particularly those exposed to gully erosion. Furthermore, one of the recommendations emphasizes the utilization of simulation programs for slopes parallel to mountain roads to assess their stability.

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