Original article

Effect Analysis of Soil Saturation and Slope Angle on the Geotechnical Stability of an Engineered Soil Slope – Bir Al-Ghanam Road, Libya

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Abstract

This study investigates the geotechnical stability of an industrial slope located parallel to the Bir al-Ghanam road in western Libya, with particular emphasis on the Effects of soil saturation and slope inclination on slope stability conditions. Field surveys were conducted to determine slope geometry, while laboratory testing was performed to evaluate variations in shear strength parameters (cohesion and internal friction angle) under different water quantities (10, 20, 30, and 50 mm). The findings indicate a progressive reduction in shear strength parameters with increasing saturation. However, the primary mechanism governing stability deterioration was the generation of pore water pressure, which significantly reduced the effective stress along the potential slip surface. Numerical simulations were carried out using RocPlane software to estimate the factor of safety under varying hydraulic scenarios. Results reveal that steep slopes (80–90°) remain relatively stable under low moisture conditions but approach critical stability states as saturation and pore pressure increase. Conversely, reducing the slope angle from 80° to 25° significantly enhanced stability due to reduced driving forces and increased resisting forces.

Keywords. Engineered Slope, Slope Stability, Cohesion and Friction Angle, Geotechnical Analysis of Slopes.

Introduction

Engineered slopes are one of the most important geotechnical challenges facing civil engineers, especially in infrastructure projects such as road and rail networks and urban development's [1]. These slopes may be created as a result of excavation and backfilling in natural terrain, or as part of an engineering design to modify the ground level, making them susceptible to a number of geotechnical hazards [2] that require careful study and comprehensive assessment. The geotechnical assessment of man-made slopes is an integrated process aimed at ensuring long-term stability and the safety of adjacent structures and individuals. This process involves several key stages, beginning with a detailed geological study of the ground formations, rock strata, and soil [3], followed by physical and mechanical analyses of the engineering properties of the soil and rocks, including shear strength, permeability, and compressibility [4].

Numerical analysis is one of the most prominent modern tools used in assessing and analyzing the stability of industrial slopes, as it allows for simulating the behavior of soil and rocks under various loading and environmental conditions with a high degree of accuracy [5]. These methods have undergone remarkable development as a result of advances in computing capabilities and numerical solution algorithms, which have contributed to enhancing their efficiency and accuracy and, in many cases, made them more representative of field reality compared to traditional analytical methods that rely on assumptions and geometric simplifications [6].

The stability of artificial and natural slopes depends on achieving a balance between the driving forces, resulting from the self-weight of soil mass, shear stresses, and external effects such as water saturation and seismic loads, and the resisting forces controlled by the mechanical properties of the slope materials [7]. The internal cohesion value and internal friction angle are among the most important properties affecting stability [8]. The equilibrium state of slopes can be expressed quantitatively using approved engineering indicators, such as the safety factor and probability of failure, based on geotechnical analysis methods and numerical modeling techniques [9].

In the study area, the construction of a new road parallel to the existing road led to the removal of parts of the natural slopes and the creation of a steep engineered slope (Figure 1). The angle of the new slope ranged from 70–90°, with an average of approximately 80°, within a soil stratum consisting of a cohesive lower layer overlaid by an uncohesive upper layer composed of poorly cohesive silty, crumbly, and clayey materials. Clear signs of water erosion were also observed on the surfaces of adjacent slopes, particularly gully erosion, reflecting the pivotal role of water saturation in accelerating geotechnical degradation mechanisms. These processes lead to a decrease in the shear strength of clayey

and silty soils and an increase in the susceptibility of loose clastic materials to disintegration and erosion, which exacerbates slope instability.

Field observations confirmed the presence of a flat, extended failure surface controlling slope instability. Although the slope material is cohesive in nature, it exhibited block-type translational failure behavior rather than rotational failure, indicating that the failure mechanism is related to the presence of a specific weakness plane acting as the main slip surface. From an engineering and geotechnical perspective, the use of high cut angles of up to 90° in such soils is not in line with accepted geotechnical standards, as it exceeds the limits of natural stability and increases the likelihood of landslides.

Figure 1: Section of cut slopes for road construction.

Based on these field indicators, this research aims to assess the geotechnical stability of the engineered slope created by the road development, considering high cutting angles and weakly cohesive soils. The study also investigates the effect of water erosion and saturation on shear strength and the probability of failure, and employs numerical analysis to estimate the factor of safety and propose engineering solutions to improve slope stability and reduce the risk of landslides. The study area is located southwest of the village of Bir al-Ghanam, south of the city of Zawiya Figure 2.

Figure 2: Location of the study area.

Methodology

This study adopted a research methodology consisting of fieldwork and data collection, laboratory tests to determine the mechanical properties of soil, and numerical modeling using specialized software for stability analysis, as follows.

Field Work

Fieldwork began on February 8, 2026, and continued for two days, using equipment and devices designed for fieldwork to collect data, describe the cut slope, determine the characteristics of the new slope geometry, and monitor field markers. The instruments used included a compass, geological hammer, Jacob's staff, magnifying glass, and various measuring rods Figure 3. Samples were also collected for laboratory study, and the most important data and measurements recorded in the field are listed in Table 1.

Figure 3: Fieldwork activities.

Table1: Slope geometry data.

targeted data	value	targeted data	value
bench width	1.5 m	effect of water	(10,20,30,50 mm)
tension crack (weakness plane)	erosion crack	slope height	7 m
distance from the road	5 m	failure plane angle	45°
distance from crust	1.5 m	upper face angle	0°
depth of the erosion crack	4m	slope face angle	80°

Laboratory tests

After collecting the sample from the location indicated in Figure 1, it was dried in an oven at 105°C for 24 hours to ensure complete removal of moisture Figure 4. In the next stage, 10 mm of water was added to the dry sample, which was then mixed thoroughly to ensure uniform water content throughout the sample. Vertical stress and shear stress tests were then performed using a direct shear tester at a constant loading rate of 0.25 mm/min [10] Figure 4. A loading frame with a constant area of 36 cm² was used for all tests, and the experiment was repeated under three different vertical weights of 4 kg, 8 kg, and 16 kg (Figure 5).

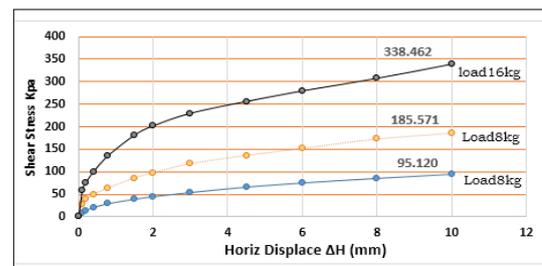*Figure 4: Direct shear test and sample preparation.*

Figure 5: Variable vertical loading (4, 8, 16 kg).

To investigate the effect of vertical load variation on the shear behavior of the sample, the original sample tests are repeated after adding water in quantities of 10, 20, 30, and 50 mm, where shear tests are affected by soil type, surface roughness, and conditions such as the presence of water and pore pressure [11]. Before conducting any slope stability assessment, comprehensive laboratory investigations are performed to evaluate the mechanical behavior of rocks and soils and to determine their resistance to compressive and shear stresses. These parameters form the basis for analyzing the stability of artificially induced slopes resulting from excavation and slope cutting during road construction. Compression and shear tests aim to determine the values of friction angle and cohesion with changing water content. Table 2 shows a sample Excel spreadsheet and data obtained from tests with an addition of 50 mm, 12% water content, and 48% saturation .

Table 2: Sample excel spreadsheet and data obtained from adding 50 mm of water to the sample

saturation:48%			water content: 12 %			date of test: 10 / 02/ 2026			
weight of sample			high of sample			sample side length			area cm³
4Kg	8Kg	16Kg	4Kg	8Kg	16Kg	4Kg	8Kg	16Kg	For all
201	197	213	2.7	2.6	2.9	6x6 cm²			36
loading rate = 0.25 mm/min				load ring constant lrc=2.1008×10⁻³					
load			normal stress			shear stress			
4kg	8Kg	16Kg	4kg	8Kg	16Kg	4kg	8Kg	16Kg
0	0	0	0	109.00	218.00	436.00	0	0
12	46	101	0.1	109.00	218.00	436.00	7.586	27.427
21	65	130	0.2	109.00	218.00	436.00	12.838	38.515
33	84	171	0.4	109.00	218.00	436.00	19.841	49.602
48	109	233	0.8	109.00	218.00	436.00	28.594	64.191
65	146	310	1.5	109.00	218.00	436.00	38.515	85.783
76	166	345	2	109.00	218.00	436.00	44.350	97.454
92	202	393	3	109.00	218.00	436.00	53.687	117.878
113	233	438	4.5	109.00	218.00	436.00	65.942	135.968
129	260	478	6	109.00	218.00	436.00	75.279	151.724
147	296	526	8	109.00	218.00	436.00	85.783	172.732
160	316	580	10	109.00	218.00	436.00	95.120	185.571

The analysis of the direct shear test results is based on the use of an Excel model to represent the linear relationship between vertical (normal) stress and shear stress, as shown in Figure 6. Through this relationship, the shear resistance coefficients, represented by the internal friction angle and cohesion, were calculated. Figure 6 shows the cohesion values when 50 mm of water is added, while Table (4) presents a comprehensive summary of the experimental data obtained from laboratory tests on soil samples at different water quantities of 10, 20, 30, and 50 mm.
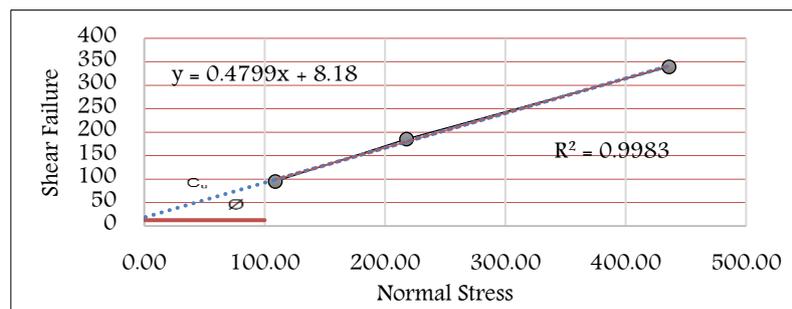

Figure 6: Relationship between normal and shear stress at 48% saturation.

Numerical modeling using RocPlane Software

RocPlane software was adopted as the primary numerical analysis tool for evaluating the stability of rock blocks and planar failures along predefined weakness planes [12]. The software is widely used in two-dimensional geotechnical analyses, as it enables the simulation of potential failure mechanisms in rock slopes and the estimation of the factor of safety (FOS), in addition to assessing support requirements when necessary [12].

RocPlane was selected because field observations confirmed a continuous planar failure surface controlling slope instability. The slope material, although cohesive, exhibited block-type translational behavior rather than rotational failure. Therefore, the failure mechanism was idealized as planar sliding along a predefined discontinuity surface, making RocPlane an appropriate analytical tool for stability assessment. The modeling process employed in this study is based on the input of three main data sets, as presented below:

Field-based slope geometry inputs

Figure 7 illustrates the field-derived inputs representing the slope geometry, including the slope face, upper slope surface, slope height, tension crack, sliding (wedge) block [13], and the failure (sliding) surface. These geometrical components form the basis for kinematic analysis and slope stability assessment (Figure 8). The most important slope geometry data entered into the program is obtained from fieldwork, Table 1.
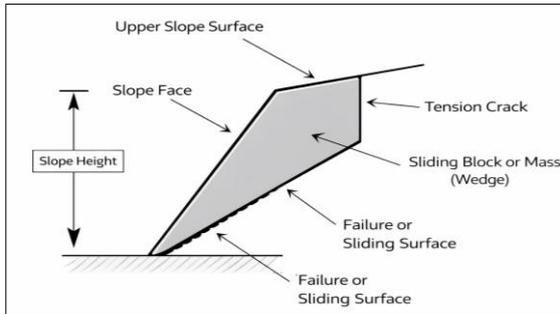

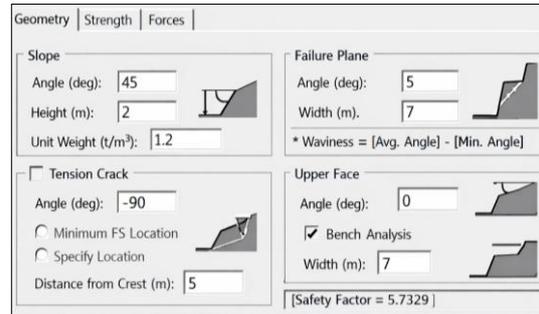*Figure 7: Field-derived inputs representing slope geometry*

Figure 8: Inputs geometry slope [13].

Shear strength parameters and External factors

These parameters include values obtained from laboratory testing, namely the cohesion (C) and the internal friction angle (φ) of the rock material along the failure surface, as illustrated in Figure 9. These parameters were determined through controlled laboratory experiments, and their values were varied for each slope simulation case in order to evaluate the Effects of mechanical property variations on the factor of safety and overall slope stability under different conditions. These factors include the driving forces that initiate movement, such as pore water pressure within rock fractures, in addition to the effects of seismic loading. The seismic effect was represented using a seismic coefficient of 0.04, based on the regional seismic characteristics of the study area (Figure 10).
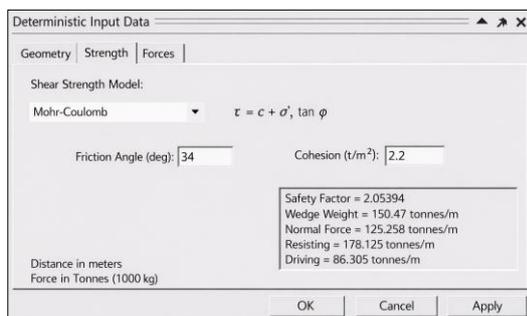

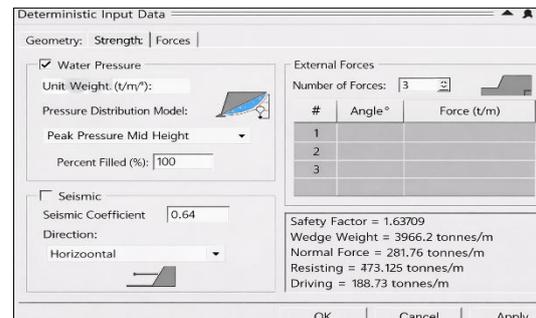
Figure 9: Shear strength inputs (C) & (φ) [13].

Figure 10: External factors [13].

Effect of slope angle reduction on the stability of the modified slope.

An engineering modification was implemented on the original slope to reduce the cut angle, as presented in Table 3. Following the modification, the slope geometry consisted of a height of 2 m, a bench width of 7 m, a slope face angle of 25°, an upper face angle of 0°, and a failure plane angle of 5°, with a tension crack (weakness plane) inclined at 90° and a horizontal distance of 5 m from the road. A numerical analysis of the modified slope was subsequently conducted using RocPlane software. The simulation was performed using cohesion and internal friction angle parameters obtained from laboratory testing under two water quantity scenarios (10 mm and 50 mm). The water pressure was incorporated in the 50 mm case to represent partially saturated conditions. The analysis results are presented in Table 5.

Table3: Modified slope geometry data.

targeted data	value	targeted data	value
bench width	7 m	effect of water	(10, 50 mm)
tension crack (weakness plane)	erosion crack -90˚	slope height	2 m
distance from road	5 m	failure plane angle	5˚
slope face angle	25˚	upper face angle	0˚

Results and Discussion

Results and discussion of laboratory tests and numerical analysis using RocPlane

Table 4 presents the results of laboratory testing and numerical modeling using RocPlane to evaluate the Effects of increasing water input (10, 20, 30, and 50 mm) on the stability of an engineered slope composed of gravelly soil with a clay fraction. The data clearly demonstrate a progressive transition in both mechanical and hydraulic behavior as the degree of saturation increases. This evolution is reflected in the gradual reduction of shear strength parameters and the emergence of pore water pressure effects, which significantly affect the effective stress state and overall slope stability.

Table 4: Results of laboratory tests and numerical analysis using RocPlane Software.

Cases	Case 1	Case 2	Case 3	Case 4
Water quantity	mm10	20mm	mm30	50mm
laboratory tests results				
Water content	6%	8%	10%	12%
Saturation	25%	32%	40%	48%
Cohesion t/m^2	10.4	9.8	8.5	8.1 t/m^2
Friction angle	$32°$	$30°$	$28°$	$25.6°$
Dry density t/m^3	1.3	1.5	1.7	1.8
RocPlane Software results				
Cases	Case 1	Case 2	Case 3	Case 4
Water peak pressure	not present	not present	tc base	mid height
Normal force t/m	9.77939	11.2839	6.35507	2.23535
Resisting force t/m	46.3263	44.4101	36.2474	32.3926
Driving force t/m	10.5943	12.2242	20.2875	20.6879
Factor of safety	4.37274	3.63295	1.78669	1.56578

In cases 1 and 2, corresponding to water inputs of 10 and 20 mm, the water content increased from 6% to 8%, and the degree of saturation rose from 25% to 32%. This led to a slight reduction in cohesion, from 10.4 to 9.8 t/m², and in the internal friction angle, from 32° to 30°, reflecting a minor decrease in shear strength. Despite this reduction, the values remained relatively high due to the granular nature of the gravelly soil with clay fraction, which maintains substantial shear resistance. The dry density increased from 1.3 to 1.5 t/m³, likely due to partial wetting and rearrangement of the soil grains, which improved particle interlock temporarily. Numerical analysis revealed no significant pore water pressure (Water Peak Pressure not present) Figures 11 and 12, indicating that the vertical stress remained largely effective. Vertical forces reached 9.779 and 11.284 t/m for cases 1 and 2, respectively, while the resisting forces were 46.326 and 44.410 t/m, compared to driving forces of 10.594 and 12.224 t/m. The large differences between resisting and driving forces resulted in high safety factors of 4.37 and 3.63, confirming the slope's extremely high stability under low saturation conditions.
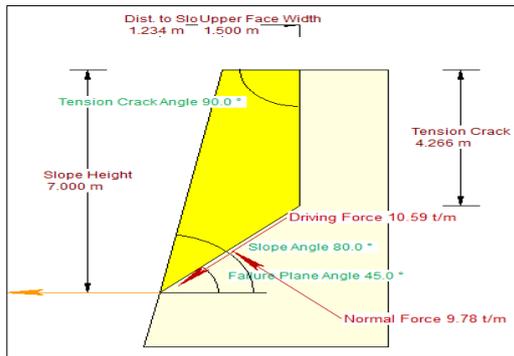
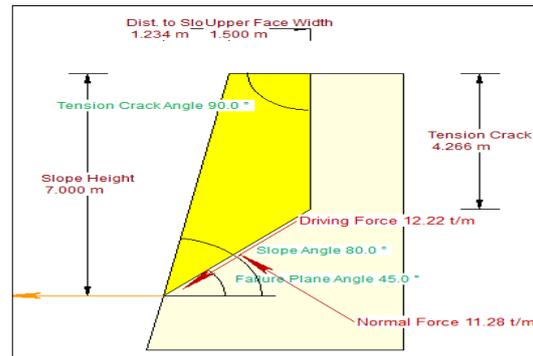*Figure 11: Slope simulated at 25% saturation*

Figure 12: Slope simulated at 32% saturation

In cases 3 and 4, at water quantities of 30 mm and 50 mm, the figures show a more pronounced change compared to the previous cases. The water content increased from 10% in case 3 to 12% in case 4, while the degree of saturation rose from 40% to 48%. At the same time, cohesion decreased from 8.5 to 8.1 tons/m², and the internal friction angle dropped from 28° to 25.6°, representing a significant reduction compared to earlier cases. At this stage, peak pore water pressure appeared. In case 3, it was concentrated at the slope base Figure 13, whereas in case 4, it shifted to the mid-height of the slope Figure 14, indicating the development of a saturation front within the soil mass. As a result, the vertical force increased to 6.355 tons/m in case 3, then decreased to 2.235 tons/m in case 4, reflecting the effect of pore pressure in reducing effective stress. The resisting force also decreased from 36.247 tons/m in case 3 to 32.393 tons/m in case 4, while the driving force remained relatively high at 20.288 tons/m and 20.688 tons/m, respectively. This convergence between resisting and driving forces led to a notable decrease in the factor of safety, from 1.79 in case 3 to 1.57 in case 4
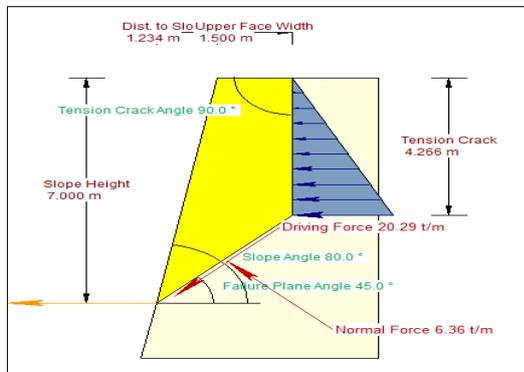

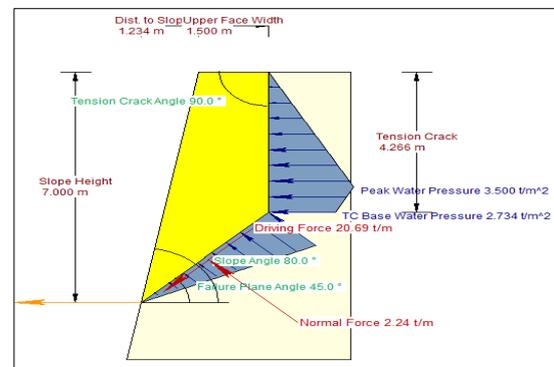*Figure 13: Slope simulated at 30% saturation*

Figure 14: Slope simulated at 25% saturation

The results indicate that the slope maintained a high level of stability under low water volumes (10 and 20 mm), despite the moderate reduction in cohesion and friction angle. A critical transition occurred with the appearance of peak pore water pressure in case (3), where the factor of safety decreased sharply from 3.63 to 1.79 (a reduction of approximately 51%), and further declined to 1.56 in case (4) as saturation increased and pore pressure propagated within the soil mass. This marked deterioration cannot be attributed solely to the reduction in shear strength parameters; rather, it is primarily governed by the Effects of pore water pressure on effective stress, which directly controls shear resistance along the potential slip surface. Mechanistically, an increase in pore water pressure reduces the effective normal stress, thereby significantly weakening shear resistance even when cohesion and friction angle remain within relatively acceptable ranges. Accordingly, saturation alone does not constitute the decisive factor in slope destabilization. Instead, the development of effective pore water pressure within the slope mass represents the primary triggering mechanism driving the system toward instability.

Predicted slope failure distance and mobilized soil volume

Based on the slope geometry presented in Table 1, the potential Failure distance under a plane failure mechanism was geometrically evaluated for a slope angle of 45°, slope height of 7 m, and erosion crack depth of 4 m. It should be noted that this plane failure approach is an approximation, as soil slopes often exhibit more complex failure behaviors, including translational or rotational mechanisms. The calculated length of the potential slip surface is approximately 9.9 m, representing the actual extension of movement along the structural discontinuity plane.

The horizontal displacement of the failed mass is estimated at approximately 7 m from the slope toe, derived from the trigonometric relationship associated with the 45° failure angle. Considering that the road is located 5 m from the slope toe Figure 1, the analysis indicates that the failed mass would reach and exceed the road by nearly 2 m in the event of full Failure. This clearly places the roadway within the direct impact zone of potential failure.

Assuming a triangular failure cross-section, the estimated failure area is approximately 24.5 m². With an erosion crack depth of 4 m, the corresponding unstable soil mass volume is approximately 98 m³. This volume represents a significant hazard magnitude, as increasing erosion crack depth proportionally enlarges the unstable block size, thereby increasing the potential kinetic energy and the associated risk to adjacent infrastructure.

Stability analysis of the modified slope

Table 5 compares the slope stability before and after modification, based on RocPlane numerical analysis, under two hydraulic conditions: Case 1 (10 mm, low saturation) and Case 4 (50 mm, partial saturation with pore water pressure). The results indicate that reducing the slope angle to 25° and adding a 7 m bench width fundamentally altered the slope's mechanical behavior and significantly improved its stability.

Table 5: Comparison of key stability parameters before and after slope modification

case parameter	Case 1 pre-modification	Case 1 modified	Case 4 pre-modification	Case 4 modified	unit
normal force	9.779	8.9666	2.2354	6.6565	t/m
resisting force	46.3263	125.385	32.3926	96.4814	t/m
driving force	10.5943	1.9535	20.6879	2.70485	t/m
factor of safety	4.3727	64.185	1.5658	35.6698	–

In Case 1 (10 mm), the safety factor before modification was high (4.37), indicating a stable slope under semi-dry conditions. After the geometric modification, the safety factor increased dramatically to 64.19, which cannot be attributed to changes in soil properties, as cohesion and internal friction remained constant, but rather to the redistribution of forces due to the slope flattening. The driving (shear) force decreased from 10.59 to 1.95 tons/m (82%), while the resisting force increased from 46.33 to 125.39 tons/m, significantly improving the ratio of resisting to driving forces. Mechanically, reducing the slope angle lowers the shear component of the weight while enhancing the effect of vertical stresses in resisting slip. Figure 15 illustrates the slope simulation after the geometric modification.
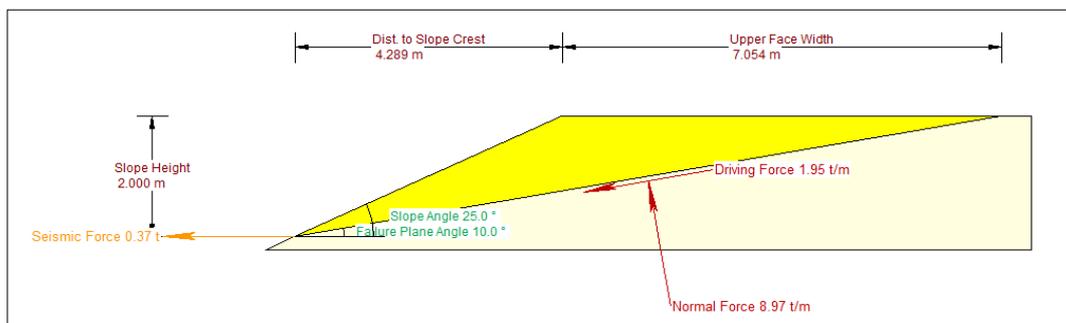

Figure 15: Simulation of the modified slope in case 1

In Case 4 (50 mm), which was critical before modification due to the development of pore water pressure and a low safety factor of 1.57, the modified slope showed remarkable improvement, with the safety factor rising to 35.67. The

driving force decreased from 20.69 to 2.70 tons/m (87%), while the resisting force increased from 32.39 to 96.48 tons/m. Vertical stress also increased from 2.24 to 6.66 tons/m, reflecting an improvement in the effective stress along the slip surface. This demonstrates that the original instability was primarily controlled by pore water pressure, reducing the effective normal stress and weakening shear resistance. By reducing the slope angle, the driving-to-resisting force ratio was drastically lowered, making the system less sensitive to pore pressure effects. Figure 16 illustrates the slope simulation under these conditions.
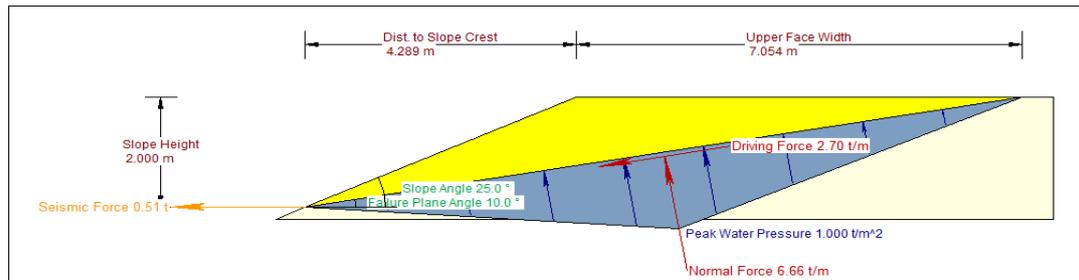

Figure 16: Simulation of the modified slope in case 4 under pore water pressure effect

The results indicate a fundamental shift in slope stability control. Before modification, the slope was hydromechanically sensitive, with pore water pressure governing effective stress and the safety factor. After reducing the slope angle and adding a terrace, stability became primarily controlled by the slope geometry, due to reduced shear stress along the slip surface, which diminished the Effects of saturation and pore pressure. Thus, Table 5 confirms that geometric modification is an effective strategy for enhancing slope stability under various conditions, and its impact can sometimes outweigh changes in shear resistance, making it a key consideration in the design and treatment of water quantity-exposed slopes.

Conclusion

This study demonstrates that the slope stability of the Engineered Slope at Bir al-Ghanam road is governed by the interaction between water saturation and slope geometry. Laboratory tests indicated that increasing water content reduces cohesion and internal friction angle. Numerical analysis further showed that the main driver of instability is the development of pore water pressure, which lowers effective stress and sharply reduces the safety factor when saturation reaches critical levels. The original steep slope (80–90°) was highly hydro-mechanically sensitive, with the safety factor approaching critical values under partial saturation. In contrast, the geometric modification reducing the slope angle to 25° and introducing a Bench Width significantly improved stability by decreasing driving forces and enhancing resisting forces under both dry and saturated conditions. These findings highlight that geometric improvement is the most practical and effective measure to enhance slope stability, especially in cohesion-deficient soils exposed to water quantity. Integrating laboratory results with numerical tools like RocPlane provides a robust framework for assessing and mitigating water quantity-induced slope failure risks.

The study recommends reducing steep cutting angles (80–90°) to safer slopes of approximately 25–35° and incorporating benches, as the results demonstrated that geometric modification is the most effective factor in increasing the safety factor and reducing driving forces. Continuous monitoring is essential, as this represents the minimum geometric requirement to limit the risk of Failure, particularly in soils highly sensitive to pore water pressure.

Conflict of interest. Nil

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