Gharyan University Journal of Engineering Science (GUJES)
Website: http://gujes.gu.edu.ly
email: gujes@gu.edu.ly

Effect of Gully Erosion on the Slope Parallel to the Al-Rujban Mountain Road NW Libya.

Aboalgasem Alakhdar*
Geological Engineering Department, Faculty of Engineering jado, Nalut University, Libya

*Corresponding author: *a.alakhdar@nu.edu.ly*

Abstract

Evaluating the impact of gully erosion on slopes parallel to mountain roads is crucial due to its role in altering slope geometry, thereby affecting overall slope stability. This study addresses the significant reduction in slope inclination from 60° (originally in 1984) to 35° caused by erosion, raising concerns about whether such changes enhance stability or increase slope fragility and collapse risk. One of the main objectives of this study was to analyze and evaluate the impact of gully erosion on slope stability, particularly by assessing changes in slope safety factors resulting from alterations in slope angles due to erosion. To achieve this, detailed field measurements were conducted to analyze the geometry of the gullies, complemented by laboratory tests using the direct shear apparatus to determine the cohesion and internal friction angle of slope materials under varying water content conditions. Additionally, the RocPlane software was employed to simulate the mechanical behavior of the slope and assess its stability under different scenarios. Results indicated that an increase in water content from 17% to 25% led to a marked decrease in cohesion (from 104 to 51 t/m²) and internal friction angle(from 22.2° to 16.5°). RocPlane analyses revealed a substantial decline in safety factors for slopes impacted by erosion and moisture—dropping to zero in some cases—while unaffected slopes maintained stability with a safety factor of 2.92. These findings highlight the critical role of gully erosion in reshaping slope geometry and compromising stability. The study recommends proactive removal of unstable rock blocks and enhancement of drainage systems to mitigate the risk of future slope failures.

Keywords: Gully erosion, Slope stability, Slope failure, RocPlane simulation.

1. Introduction

The movement of materials on the slopes of mountain roads is one of the most hazardous geological phenomena due to the risks it poses to road users This risk increases with rapid and sudden movements, which amplify the resulting damage [1] The causes of slope failures on mountain roads are varied, including the slope geometry and the impact of rainfall [2] Water plays a significant role as one of the primary triggers, affecting slope stability both directly and indirectly, with one of its most prominent effects being gully erosion [3]Gully erosion is defined as the process of rock and soil erosion caused by water flowing through natural gullies on mountain slopes [4] This process gradually removes soil, weakening slope cohesion, particularly in areas composed of soil and rock debris [5] Erosion also deepens gullies, creating steeper slope angles that concentrate runoff in specific areas, which increases their fragility and susceptibility to collapse [6,7] As the depth of the gullies increases, cracks and voids form, further reducing the cohesion of both surface and subsurface layers, which can lead to partial or full-scale collapses [8] Additionally, gullies fragment slopes into small, unstable blocks, heightening the likelihood of independent movement [9] Heavy rainfall accelerates this process by saturating the soil with water, further intensifying erosion and landslides [10] Clay, sandy

Gharyan University Journal of Engineering Science (GUJES)
Website: http://gujes.gu.edu.ly
email: gujes@gu.edu.ly

soils, and rocky debris are particularly vulnerable to this phenomenon [11] Gully erosion does not only result in morphological changes; it also leads to the destruction of the structural integrity of slopes, increasing their susceptibility to collapse and posing a threat to mountain roads [12] The research issue arises from the observation of erosion gullies on the slopes parallel to the Rujban mountain road, where the slope is composed of rocky debris of varying sizes Figure 1 It was noted that erosion had created a new slope angle of 35° within the gullies, compared to the original angle of 60°, This observation raised two key questions: What is the effect of gully erosion on slope stability? Can erosion, contribute to slope stability by reshaping slopes into more stable angles?. Consequently, the aim of this research is to analyze and evaluate the impact of gully erosion on slopes parallel to mountain roads, and to determine the slope safety coefficients with changes in slope angles resulting from erosion.

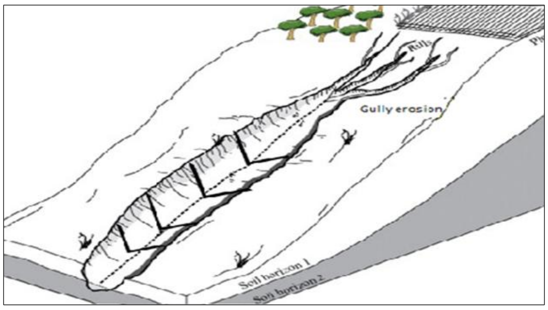

Figure 1: Gully erosion model [13]

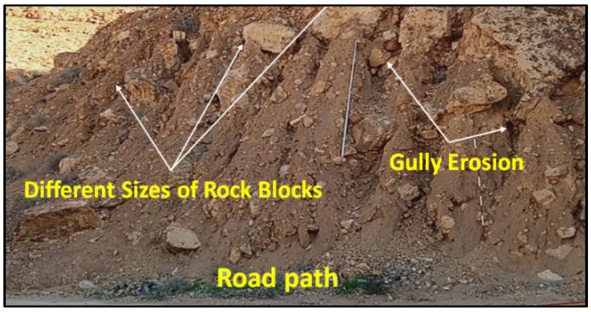

Figure 2: Gully Erosion On study area

The study area is situated on the northern edge of Jebel Rujban, with the road extending northward to connect to the Aziziya-Nalut road Figure 3 Geologically, as shown in Figure 3, the study area lies between the Sidi as Sid Formation [14] and the Kikla Formation [15] The rocks in this area represent diverse sedimentary environments, formed through cycles of sea advance and retreat, where both continental and marine species were deposited in a transitional environment [16], In the study area Figure 3, the stratigraphic sequence culminates with the Qasr Taghrana Formation, which is dated to the Upper Cretaceous [17].

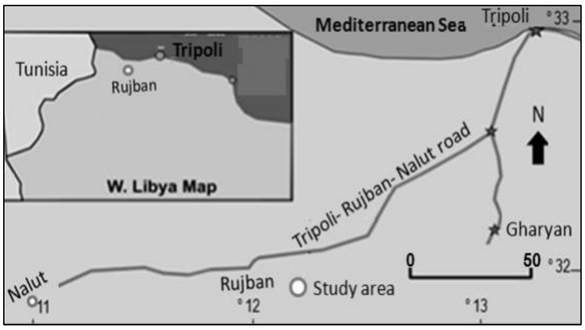

Figure 3: Location of the study area [18]

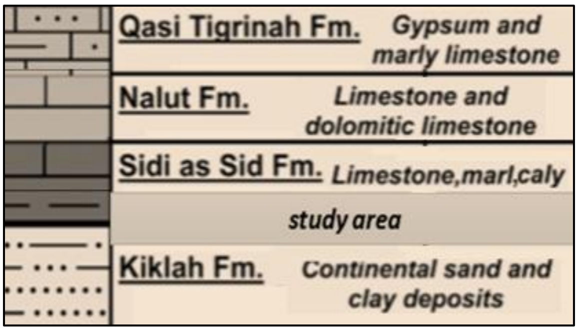

Figure 4: Outcrop formations Rujban Area [18]

Gharyan University Journal of Engineering Science (GUJES)
Website: http://gujes.gu.edu.ly
email: gujes@gu.edu.ly

2. Material and Methods

- **Field study phase:** The field study was conducted to collect data on slope geometry Measurements and field data were recorded in two cases: first, when the slope inclination angle was 60°, representing the natural slope cut in 1984 and considered unaffected by gully erosion; and second, at an angle of 35°, "These results reflect the effects of water erosion within the gullies. The slope geometry data are shown in Table 1. Accurate field measurements are crucial for realistically representing slope conditions and enhancing the reliability of simulation models.

Table 1: On-Site Slope Geometry Data

Cases	A	B	C	D
Slope Condition	**unaffected by erosion**		**affected by erosion**	
Water Quantity	30mm	60mm	30mm	60mm
Slope Height	9 m	9 m	9 m	9 m
Slope Angle	60°	60°	35°	35°
Failure Plane Angle	35 °	35 °	1°	1°
Upper Face Angle	10°	10°	10 °	10 °
Bench Width	6m	6m	m3	3m
Seismic Coefficient	0.04	0.04	0.04	0.04
Tension Crack	90 °	90 °	90 °	90 °
Water Pressure	On Failure Plane	On Failure Plane	at toe of slope	at toe of slope

One of the important field data recorded is the information on erosion gullies, which includes the following variables: width of the gully at the surface, depth of the gully at the surface, length of the gully, and affected area these data are presented in Table 2. The aim of calculating these variables is to determine the Gully Erosion Rate GER, measured in m³/m²/year, which is calculated using the relationship outlined in (1) [19].

Table 2: Field Data and Gully Erosion Analysis

Slope Length	Slope Height	Total Gullys Length (L)	Average Gullies Width (W) m	Average Gullys Depth	Time Period Years - T
200 m	9 m	960 m	70 cm	80 cm	40 Years
Affected Area		Gully Length	Gully Width (W) m	Gully Depth	Road Cut 1984
1800 m^2		960 m	0007 m	0008 m	

$$GER = \frac{V}{T \times A} \quad (1)$$

Where:
V = Gully volume (m³),
T = Time period years,
A = Affected area (m²)

The volume of groove erosion V m³ is calculated by the relationship (2) [19]

$$V = \frac{1}{2 \times W \times D \times L} \quad (2)$$

Where:
L= Gully Length (m)

W = Gully Width at the surface (m),
D = Gully Dept**h (m)**

Using Equation 2, the volume of gully erosion was calculated as 0.02688 m³. Substituting into Equation 1, the gully erosion rate (GER) was determined to be 3.733×10^{-7} m³/m²/year. Comparison with Table 3 shows a very low erosion rate, indicating minimal fluting impact in the area. A detailed interpretation will follow.

Table 3: Gully Erosion Severity Classification [20]

Gully Erosion Rate m³/m²/year	Classification
Less than 00001	Very Weak
00001 – 00005	Weak
00005 – 0001	Moderate
0001 – 0005	Severe
Greater than 0005	Very Severe

- **Laboratory study phase:** A sample of rock debris from a slope affected by gully erosion was collected at a depth of 30 cm and transported to the lab The sample was dried in an oven at 120°C for 24 hours, and then 30 mm of water was added for homogenization Vertical and shear stress tests were performed using a direct shear apparatus with a loading rate of 025 N/s and a 36 cm² loading frame, as described in reference [21] The test aimed to determine cohesion and friction angle, with the linear relationship between normal and shear stress recorded using a pre-prepared Excel curve Figure 5, The test was conducted with three weights (4 kg, 8 kg, and 16 kg) Figure 6 According to reference [21], a collapse of the rock debris occurred at a water volume of 80 mm, with internal saturation reaching 65%, leading to the loss of internal cohesion and a value of 0 t/m² The extracted values for (C and Ø) are listed in Table 3, and these data are essential for input into the RocPlane program

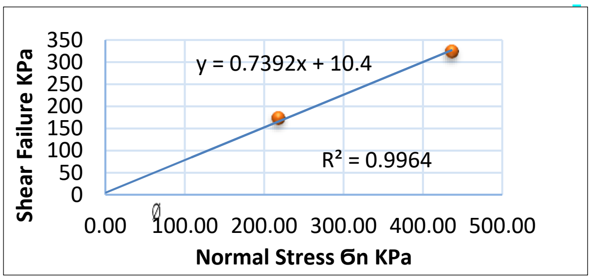

Figure5: Relationship between normal &shear stress

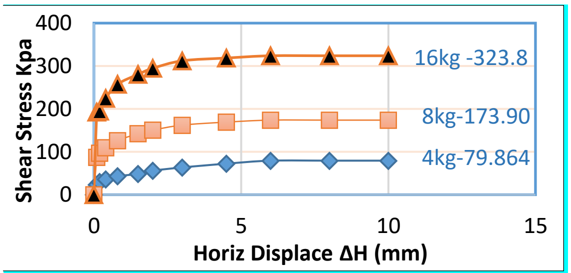

Figure 6: Variable horiz sample at load(4,8,16 kg)

The same tests were repeated on the original specimen with the addition of 60 mm of water The results from the laboratory study are listed in Table 3 Direct shear tests are influenced by factors such as rock type, surface roughness, water presence, and pore pressure [22].

Gharyan University Journal of Engineering Science (GUJES)
Website: http://gujes.gu.edu.ly
email: gujes@gu.edu.ly

Table 4: Data and results obtained from the laboratory study

Water quantity	30mm	60mm
Saturation %	17%	25%
Cohesion C	10.4 t/m^2	5.1 t/m^2
Friction Angle Ø	°22.2	°16.5
Unit Weight	1.7 g/cm^3	2.1 g/cm^3

- **RocPlane software phase:** An interactive software tool for assessing the stability of slope components. The tool enables users to estimate the required support to achieve a specific safety factor in slope analysis and design by generating 2 and 3D models [23]. Figure 7. The software relies on several inputs, including:Slope geometry Figure 7, based on the data listed in Table 1.Cohesion and friction angle Figure 8, listed in Table 4.External forces, such as water pressure and the seismic coefficient of the study area [24].

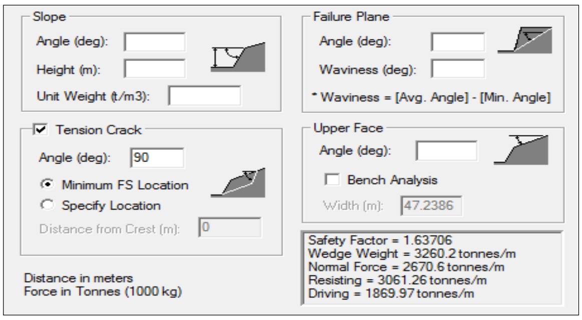

Figure7: Inputs Geometry Slope

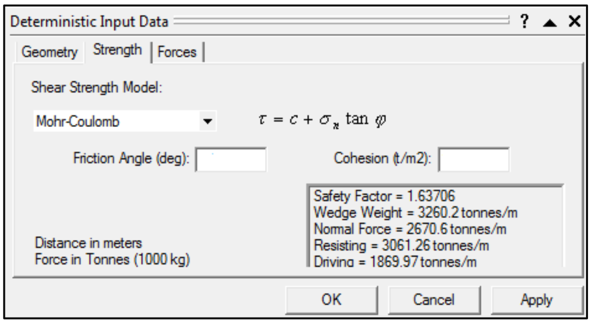

Figure8: Inputs C & Ø Angle.

To determine whether the slope is stable, the coefficient of safety, derived from the relationship between the resistive force and the impulse, is compared with Table 5. This table categorizes the stability of slopes, both parallel and adjacent to mountain roads [25].

Table 5: Highways slope stability classification [25]

Slope stability	actor of safety
Stable	> 1.5
Intermediate stability	1.25 – 1.5
Precarious stability	1 – 1.25
Instable	<1

3. Results and Discussion

The studied slope consists of rocky debris of various sizes, primarily composed of limestone, clay, and marl rocks from the Sidi as Sid Fm of the Ain Tabi Member. During excavation, these rocks were displaced, and the debris was used to form a new artificial slope made of soil, clay, and rock blocks. The grooves observed in the slope reflect the effect of rainfall, which contributed to lateral erosion of the grooves, removing soil and debris from the sides and bottoms of the rock blocks Figure 9.This erosion, affects the stability of the rock blocks, soil, and clay, particularly in the absence of protective concrete barriers. Additionally, gully erosion has altered the slope's geometry, with an inclination angle of 35° within the gullies, indicating the strong impact of this process. The Gully Erosion Rate (GER) is 3733 × 10^{-7} m^3/m^2/year, which is categorized as "very weak" Table 3, meaning the rate of material loss is relatively slow and does not result in the formation of new gullies or channels.

Figure 9: Section of the Slope Affected by Gully Erosion

This suggests that the erosion is gradual and continuous, but not significant enough to cause rapid collapses or drastic changes to the slope in the short term. Moreover, the gullies have contributed to the formation of new stabilizing angles within the slope. However, the greatest risk lies in the potential collapse of large and medium-sized rock blocks that are currently stabilizing the slope, especially within the gullies. It is expected that continued erosion over time will lead to the collapse of these rock blocks, particularly with external factors like rainfall. Additionally, the mud and collapsed debris have blocked the water drainage channels parallel to the road path Figure 9, some of the rock blocks have collapsed, serving as an indicator of the weakened state of the slope. The field study reflects the impact of geomorphological and Hydrological factors on the stability of the studied slope. This is consistent with the results of the laboratory tests conducted using the direct shear device. Laboratory data indicate that increasing the water content from 17% to 25% led to a decrease in cohesion from 104 t/m² to 51 t/m² Table 4, while the internal friction angle decreased from 22.2° to 16.5°.This finding is directly related to the field study results, which showed that the flow of water inside the gullies caused erosion of their sides, removing soil and debris. This erosion led to the collapse of rock blocks, soil, and clay, particularly in the absence of concrete barriers. These observations are consistent with the laboratory results, which indicated that an increase in water content reduces shear strength and increases the risk of collapses. This makes large and medium-sized rock blocks, located either on the slope or inside the gullies, more susceptible to future collapse. Moreover, the laboratory data confirmed that the low internal friction angle of 16.5° Table 4 reflects the weak resistance of the slope components to collapse. This is connected to the changes in slope geometry, as the angle of inclination inside the gullies reached 35°, suggesting that gully erosion plays a major role in reshaping the slope's topography and affecting its

Gharyan University Journal of Engineering Science (GUJES)
Website: http://gujes.gu.edu.ly
email: gujes@gu.edu.ly

stability. The closure of drainage channels parallel to the road due to debris is consistent with the effect of increasing pore pressure from the high water content, which leads to the disintegration of soil and rock debris. Consequently, the accumulation of eroded materials in low-lying areas may further increase the risk of future collapses due to poor water drainage. The data in Table 6 present a slope analysis using Rocplane software.

Table 6: Rocplane software output

Cases	A	B	C	D
Slope Condition	**Unaffected by erosion**		**affected by erosion**	
Water Quantity	30mm	60mm	30mm	60mm
Normal Force	47.1065 t/m	0 t/m	8.16441 t/m	10.0778 t/m
Resisting Force	93.2851 t/m	0 t/m	43.4434 t/m	22.6553 t/m
Driving Force	31.9539 t/m	43.7766 t/m	0.470195 t/m	0.580829 t/m
Factor of Safety	2.92	0	92.3945	39.0051

In Case-A, Figure 10, the slope unaffected by erosion, indicating good stability at this location. The Water Quantity in this case was 30 mm, which is relatively low and helps maintain stability. Additionally, the vertical force was 47.106 t/m, reflecting a moderate weight effect on the slope. Furthermore, the resistive force in Case A was the highest 932.8 t/m among all cases, contributing to greater stability. The safety factor reached 2.9 confirming that the slope in this case is stable, Table 5.

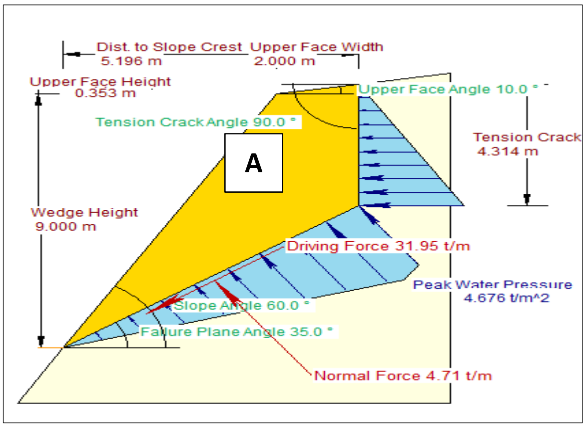

Figure 10: Slope Unaffected by Erosion at 30mm

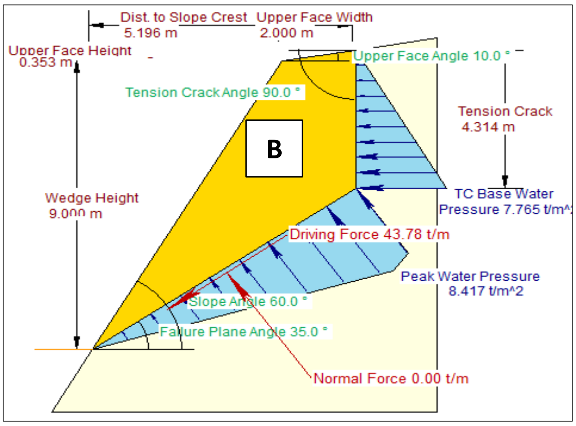

Figure 11: Slope Unaffected by Erosion at 60mm

On Figures 10 and 11, It is observed that the effect of water pressure is concentrated in two locations. The first is in the vertical direction (tension crack - 90°, Table 1), extending from the top surface to a depth of 4.31 m. This position is considered a weak point behind the wedge and can only be observed in the field. The second place of water pressure concentration is on the failure plane, where the pressure value varies depending on the amount of water.In case A, the water pressure is 4.676 t/m³, while in case B, it is 8.41 t/m³.

In Case-C, Figure 12, the slope was affected by gully erosion, with a water amount of 30 mm, the same as in Case A. The vertical force was 8.16 t/m, indicating a greater weight effect on

Gharyan University Journal of Engineering Science (GUJES)
Website: http://gujes.gu.edu.ly
email: gujes@gu.edu.ly

the slope compared to Case A. However, the resistive force was lower than that in Case A, suggesting that stability was slightly affected by erosion. Nevertheless, the safety factor in this case was significantly high (92.39), indicating that the slope is stable Table 5.

In Case-D, Figure 13, the slope affected by gully erosion, with a Water Quantity of 60 mm, similar to that in Case B. The vertical force in this case was 10.07 t/m, indicating greater pressure on the slope due to weight. However, the resistive force was 2,266 t/m, which is lower than in Case A, suggesting that the slope is relatively weak. Nevertheless, the safety factor in this case was 39.01, indicating relatively good stability compared to Case B.

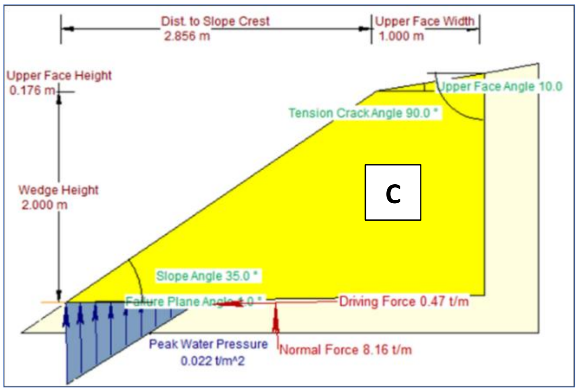

Figure 12: Slope affected by gully Erosion at 30mm

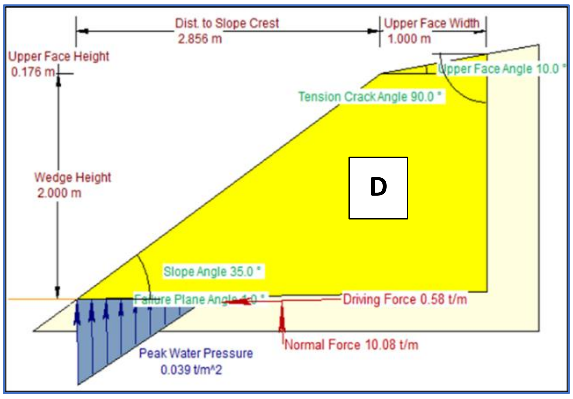

Figure 13: Slope affected by gully Erosion at 60mm

4. Conclusion

The study results revealed that gully erosion contributed a pivotal role in the stability of the slope parallel to the Al-Rujban mountain road, directly affecting the slope's geometry. Additionally, gully erosion indirectly contributes to the collapse of rock masses and debris, as confirmed in the analysis. Water-induced gully erosion leads to the erosion of gully sidewalls, exposing rock masses and soil to the risk of collapse, particularly in areas lacking engineering support structures such as concrete barriers. Furthermore, the effects of erosion were evident in the formation of new slope angles, with the inclination angle inside the gullies reaching 35°, reflecting the significant changes caused by erosion in slope geometry. Rocplane software analysis assessed slope stability under water erosion. Findings showed that increased water content reduces cohesion and friction, weakening slope resistance. Pour water pressure from excess moisture raises landslide risks, especially without proper drainage. Hydrological factors significantly affect stability, as large water volumes alter slope forces. Despite its "very weak" erosion rate, gully erosion causes gradual instability, posing a long-term collapse risk. The study recommends regular monitoring and removal of unstable rock masses

References

[1] M. G. Winter, "Landslide hazards and risks to road users, road infrastructure and socio-economic activity," in XVII European Conference on Soil Mechanics and Geotechnical Engineering, Reykjavík, Iceland, vol. 1, no. 6, pp. 196–343.2019.

[2] H. Wang, G. Yuan, Z. Huang, J. Dong, and Y. Wei, "Study on deformation and failure characteristics of oblique-cut locked rock slope under rainfall conditions," *Scientific Reports*, vol. 14, no. 1, pp. 1-18, 2024. https://doi.org/10.1038/s41598-024-64329-5

[3] C. Geitner, A. Mayr, M. Rutzinger, M. T. Löbmann, R. Tonin, S. Zerbe, et al., "Shallow erosion on grassland slopes in the European Alps–Geomorphological classification, spatio-temporal analysis, and understanding snow and vegetation impacts," Geomorphology, vol. 373,107446, pp. 1-19, 2021.

[4] N. N. Ukatu, "Factors of gully expansion in Nanka gully site: Orumba North Local Government Area (LGA), Anambra State," Ph.D. dissertation, Dept. of Geography, Univ. of Nigeria, Nsukka, 2019.

[5] S. Ni, J. Peng, J. Wang, L. Zhu, D. Wang, and C. Cai, "Impacts of slope morphological evolution on subsequent erosion for a coarse-textured soil," Geoderma, vol. 430, 116320, PP.1-12, 2023.

[6] O. Fashae, R. Obateru, A. Olusola, and D. Dragovich, "Factors controlling gully morphology on the quartzite ridges of Ibadan, Nigeria," Catena, vol. 212, pp. 106127, 2022

[7] M. J. Kirkby and L. J. Bracken, "Gully processes and gully dynamics," *Earth Surface Processes and Landforms, vol. 34, no. 14, pp. 1841–1851, 2009.

[8] J. Xia, L. Zhang, P. Ge, X. Lu, Y. Wei, C. Cai, and J. Wang, "Structure degradation induced by wetting and drying cycles for the hilly granitic soils in collapsing gully erosion areas," Forests, vol. 13, no. 9, pp.1-16, 2022. https://doi.org/10.3390/f13091426

[9] X. Liu, X. Zhang, H. Gao, G. Wang, and S. Zhang, "How climate-induced wetting–drying cycles contribute to gully erosion: A case study from southern China," Catena, vol. 232, Article 107422, 2023. https://doi.org/10.1016/j.catena.2023.107444

[10] O. Rahmati, Z. Kalantari, C. S. Ferreira, W. Chen, S. M. Soleimanpour, M. Kapović-Solomun, and N. K. Kazemabady, "Contribution of physical and anthropogenic factors to gully erosion initiation," Catena, vol. 210, pp.1-12, 2022. https://doi.org/10.1016/j.catena.2021.105925

[11] A. Goudie, "Water Erosion and Mass Movements," in Landscapes of the Anthropocene with Google Earth, Cham: Springer, pp 191–219, 2023. https://doi: 10.1007/978-3-031-45385-4_9.

[12] J. Li, Y. Deng, X. Duan, C. Cai, and S. Ding, "Does joint structure promote the development of gully erosion?," Catena, vol. 214, 2022. https://doi.org/10.1016/j.catena.2022.106233

[13] B. Wang, Z. Zhang, X. Wang, X. Zhao, L. Yi, and S. Hu, "Object-based mapping of gullies using optical images: A case study in the black soil region, Northeast of China," Remote Sensing, vol. 12, no. 3, pp 1–20, 2020. https://doi.org/10.3390/rs12030487

[14] A. Alakhdar, "Effect of fault on the physical properties of the ain tabi member: a case study of al-qwasim mountain road slopes," University of Zawia Journal of Engineering Sciences and Technology, vol. 22, pp. 197–207, 2024. https://doi.org/10.26629/uzjest.2024.18

[15] E. Alfandi, Early Mesozoic Stratigraphy, Sedimentology and Structure of the Gharian Area, North Western Libya, Ph.D. dissertation, Plymouth Univ., 2012, pp. 1–344.

[16] R. Almagtuf and A. Alakhdar, "Analysis of the Stability of Nalut Formation Outcrops Parallel to Al-Rujban Mountain Road-NW Libya," AlQalam Journal of Medical and Applied Sciences, pp. 213–220, 2025. https://doi.org/10.54361/ajmas.258133

[17] M. T. El-Bakai, "Petrography and palaeoenvironment of the Sidi as Sid Formation in Northwest Libya," Petroleum Research Journal, pp. 9–26, 1997.

[18] K. Abdunaser., "The geologic contribution to the mountain slopes instability and its effect on rockfall hazards: A case study to the Zintan Road, Jabal Nafusah, Libya," in Proc. Fifth Conf. for Engineering Science and Technologies (CEST), Jadu, Libya, May 20–22, 2022.

[19] A. Osore and A. Moges, "Extent of gully erosion and farmer's perception of soil erosion in Alalicha Watershed, Southern Ethiopia," J. Environ. Earth Sci., vol. 4, pp. 74–81, 2014.

[20] R. P. C. Morgan, Soil Erosion and Conservation, 3rd ed., Blackwell Publishing, 2005, pp. 1–448.

[21] A. Alakhdar and M. Albarshani, "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," in Sebha University Conference Proceedings, vol. 3, no. 2, pp. 28–33, Oct. 2024. https://doi.org/10.51984/sucp.v3i2.3118

[22] A. R. TolouKian, J. Sadeghi, and J. A. Zakeri, "Large-scale direct shear tests on sand-contaminated ballast," Proc. Inst. Civ. Eng. - Geotech. Eng., vol. 171, no. 5, pp. 451–461, 2018.

[23] A. Alakhdar, "Evaluating the stability of parallel rock discontinuities along al-mishar road in the bir al-ghanam area nw libya," Journal of Pure & Applied Sciences, vol. 22, no. 3, pp. 102–107, 2023. https://doi.org/10.51984/jopas.v22i3.2755

[24] A. Alakhdar and A. Abudiena, "Stability study of sandstone slope parallel to the abu rashada mountain road in gharyan area nw libya," Journal of Pure & Applied Sciences, vol. 21, no. 4, pp. 104–110, 2022.

[25] P. S. Andrade and A. Saraiva, "Stability analysis of road slopes in central Portugal," 2006. https://media.geolsoc.org.uk/iaeg2006/PAPERS/IAEG_483.PDF