Original article

Analysis of the Stability of Nalut Formation Outcrops Parallel to Al-Rujban Mountain Road-NW Libya

Reda Almagtuf[1*], Aboalgasem Alakhdar[2]

[1]*Department of Geology, Faculty of Science, University of Zawia, Zawia, Libya*
[2]*Department of Geological Engineering, Faculty of Engineering, Nalut University, Jado, Libya*
Corresponding Email. a.alakhdar@nu.edu.ly

Abstract
The slopes parallel to mountain roads are affected by both natural and human factors, such as slope-cutting processes during road construction, making slope stability assessment essential. Factors like rainfall and improper rock-cutting angles contribute to slope weakness and rockfalls, causing road damage and posing risks to users. This study aims to assess the stability of the Nalut Formation outcrops along the Al-Rujban mountain road. A field study was conducted, where the site was coded (L-R-R-21), and two locations (L1, L2) were selected to collect samples and measure fractures and joints, as well as study rock mass properties, including the Rock Quality Designation index. Results showed that site L1 contains three joint systems (S1, S2, S3), where S1 and S2 intersect at a 90° angle, reducing the RQD value to 44%, classifying it as "poor." The joint system indicated a wide spacing between rock masses, with an average joint spacing (JS) of 89 cm, categorizing it as widely spaced. Slope cutting at 90° led to rockfalls. The lower rock formations were smaller due to random fractures, while the upper formations were larger and more hazardous when collapsing. The study recommends removing fallen blocks and regularly monitoring the slopes to ensure user safety.
Keywords: Slope Stability, Nalut Formation, Joint Spacing, Fractures, Joints.

Introduction

Slopes are crucial geomorphological features with varying formation, composition, and stability, influenced by natural and human-induced factors. Their stability depends on material coherence, and disturbances such as excavations and explosions can lead to instability [1-2]. Gravity-driven movements like rockfalls, landslides, and soil creep differ in speed and impact, with rockfalls causing significant damage [3-4]. Rainfall and climatic conditions accelerate slope failures, especially when vegetation is absent [5-6]. Over time, mechanical and chemical weathering weakens rock cohesion, creating fractures and joints in sedimentary rocks [7]. This leads to shifts in the equilibrium angle (85°-90°), resulting in rockfalls and other failures [8]. In arid regions, temperature fluctuations cause mechanical disintegration [9]. The research focuses on the stability of slopes along the Al-Rujban mountain road, where disturbances in the equilibrium angle can lead to hazards. These movements can disrupt traffic, block drainage, and damage vehicles. Given the weaknesses of the Nalut Formation along the road, this study aims to assess its stability, identify the key weathering and erosion factors, and predict likely movements. The study area is geographically located north of Al-Rujban, starting at the end of the village of Qasr Dallah and extending along the Al-Rujban mountain road. The study area is located between latitudes (N 31° 59'59") (N 31° 59'17"), and longitude. (E 12° 08'07"), (E 12° 06'07") Figure1. The study area is part of the Jebel Nafusah Mountain range in northwest Libya, bordered by the Mediterranean Sea to the north, the Jafara Plain, and extending east to ALKhoms and south to the Ghadames Basin. It also reaches the Tunisian border in the west. The region's rocks reflect diverse sedimentary environments shaped by cycles of sea advance and retreat, depositing a variety of sedimentary rocks from continental to marine types, in a transitional environment [10]. The geological sequence begins with the Kurrush Formation from the Lower Triassic, continuing to the Cenozoic Era with the Zimam Formation. In Al-Rujban, the sequence ends with the Qasr Tigrinnah Formation, dating to the Upper Cretaceous (Sinomani - Turuni) [11].

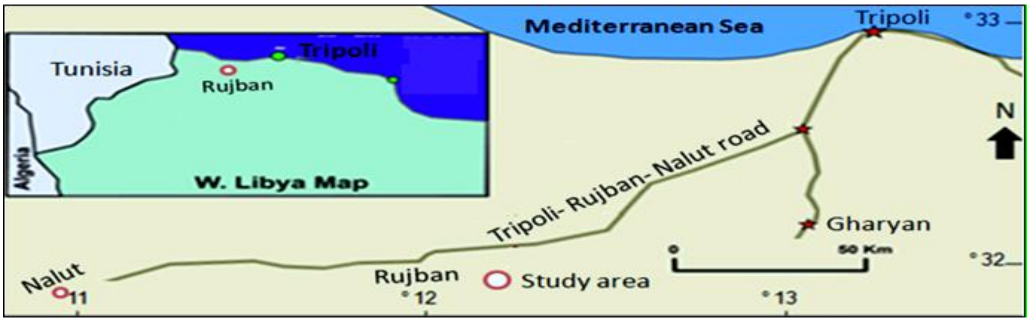

Figure 1. Location of the study area [12]

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Methods

The study was conducted in stages as shown by the following presentation.

First stage

This stage included collecting information about the research problem, getting to know the study area closely by reviewing related literature and evaluating its suitability for the objectives of the current study, and then collecting preliminary data through field visits to move in the right direction in support of the research journey.

Second Stage: Field Study

To collect data, a field study was conducted; the field study was the basis for simulating the reality of the slopes. This phase was concerned with field measurements and conducting descriptive and analytical surveys of the reality of the slopes. This phase resulted in the collection of data and information on the research problem and the identification of evidence of the movement of materials, the expected geomorphological risks, as well as making predictions based on field data and evidence. This stage relied on the field study to make measurements related to the geometric properties of rock masses along a survey line of 200 meters distributed at two heights. To evaluate the physical and mechanical properties of the rock outcrops Parallel to the road, the clear outcrops closest to the mountain road were selected. To distinguish the present study from previous studies, a general code was chosen for the study site (L-R-R-21), with the L standing for Location, the R for Road, the R for the term Rujban, and the number 21 for the year of the study 2021 Figure 2.

Figure 2. Location of the studied slopes (L1-R-R-21) & (L2-R-R-21)

Field tests conducted in the field to obtain the geometric properties of collapsed masses and healthy massif include manual pressure test and geological hammer to estimate rock strength [13]. Here is a summary of the reported results Table1.

***Table 1. Estimation of sound rock strength* [13].**

Intact rock strength	Description
< 1.25 MPa	Crumbles in hand
1.25 – 5 MPa	Thin slabs break easily in hand
5 - 12.5 MPa	Thin slabs break by heavy hand pressure
12.5 – 50 MPa	Lumps broken by light hammer blows
50 – 100 MPa	Lumps broken by heavy hammer blows
100 – 200 MPa	Lumps only chip by heavy hammer blows
> 200 MPa	Rocks ring on hammer blows. Sparks fly

A total of 120 samples were tested, including 60 samples at the top of the slope (L1-R-R-21). Rock strength of sound rocks, i.e., rocks at their source, ranged from 200-100 MPa, meaning that the blocks were cut only with heavy hammer strokes. (See Table 1 above). This explains the presence of some collapsed masses that have not changed in the shape in which they collapsed and thus demonstrate the strength of the rocks. The test was carried out using a geological hammer on sound rocks along the slope (L2-R-R-21) with 60 samples. Multiple estimates were recorded. When calculating the average values, the sound strengths ranged from 100-50 MPa because the masses are broken by heavy hammer strokes.

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Third stage
This stage was concerned with studying the stability of the slopes Parallel to the road. The study of the geometric properties of the surfaces of cracks and joints was relied upon as weak areas of rocks. The most important of these geometric properties are:

Physical Properties
Roughness
It means the shape of the slit surface. The description depends on the origin of the surface formation. It includes three original types: smooth surfaces, rough surfaces and very rough surfaces. Other scales that describe the shape of the slit surface branch out of it. The rougher the surfaces, the less the undulations on the surface of the slit, while in soft surfaces there is no cohesion, so the movement is more frequent, especially with the presence of a stimulus for movement such as water [14]. Slit surfaces are classified in Table 2

Table 2. Classification of slit surface shapes [14].

Term	Description
Very rough	Near vertical steps and ridges occur
Rough	Some ridge and side-angle steps are evident; asperities are clearly visible
Slightly rough	Asperities on the discontinuity surfaces are distinguishable and can be felt
Smooth	Surface appear smooth and feels so to the touch.
Polished	Visual evidence of polishing exists, or very smooth surface
Slicken sided	Polished and often striated surface that results from friction

Size of joints and continuity
This property distinguishes cracks from joints and their impact on rock masses. Joints are classified as continuous or intermittent, with greater depth leading to weaker rock masses [15].

Table 3. Classification of the size of joints based on their length [16].

Joint length	Description
Less than a meter	Very Short
1-3 meters	Short
3-10 meters	Medium Length
Longer than 10 meters	Very Long

Separation
It refers to the amount of separation of the mass or parts thereof from the original mass. Field measurements obtained from the classification developed by the Geological Society of London (1977) table 4.

Table 4. Classification of separation Source: Dafalla & Malik, 2015

Term	Aperture
Wide	>200 mm
Moderately wide	60 – 200 mm
Moderately narrow	20 – 60 mm
Narrow	6 – 20 mm
Very narrow	2 – 6 mm
Extremely narrow	0 – 2 mm
Tight	Zero

Infilling materials
They are the materials between the spaces. These materials do one of two things: either they contribute to the stability of the rock masses or they have a role in movement. In both cases, the amount of stability or motion depends on the type and size of the material and fragments (Table 5).

Table 5. Infilling materials and their properties [16]

Type of Filling	Properties
Chlorite; talc	Graphite Very low friction materials, in particular when wet.
Inactive clay materials	Weak, cohesion materials with low friction properties
Swelling clay	Exhibits a very low friction and loss of strength together
Calcite	May dissolve, particularly when being porous or flaky.

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Gypsum	May dissolve
Sandy or silty	Materials Cohesion less, friction materials
Epidote; quartz	May cause healing or welding of the joint

Mechanical properties

Cracks and joints in rock masses are a natural phenomenon and are considered one of the most common secondary structures due to natural factors and lack any visible movement. Although they can occur alone, they often occur as common groups and systems and can be measured by studying physical and mechanical properties. The mechanical properties of rock masses can be measured in the field or in the laboratory. In this study, field measurements are relied upon to study mechanical properties. Field measurements are more simulated to the reality of rock mechanics. They are based on the measurement of mechanical properties, especially the measurement of the strength or durability of the rock (RQD) and the property of the joint system cracks. Here is an account of these field measurements.

Joint Spacing (JS): It is defined as the distance in centimeters between a joint and the joint Parallel to it. The system of joints is not necessarily equal in distances, as they may be spaced in the same rock unit. The spacing between the joints in igneous rocks is less than 20 cm, unlike sedimentary rocks, where the spacing may reach 100 meters and are either parallel to the application surfaces or cut the first group at an angle of 90° [17]. Measuring spacing is of great importance in assessing the structure of rock sections, as joints reduce the strength of rocks. Joint spacing is calculated in two ways, as follows Table 6.

a. If a joint is one-way, i.e. regular, then it is calculated by Equation (1)

$$Sa = S1 + S2 + S3 + \cdots .. \frac{1}{\mathrm{SN}} .. \text{Equation (1)}$$

where
Sa = (JS) = Average distances between joints
S1 = Distance between the first joint and second joint
S2 = Distance between the second joint and third joint
N = Number of spaces between joints

b. If three systems of joints intersect at different angles, they are calculated by Equation (2)

$$Sa = js = set1 + set2 + set3/3 .. \text{Equation (2)}$$

Where
Set 1 The first joint system is calculated by equation 1
Set 2 The second joint system is calculated by equation 1
Set 3 Third joint system calculated by equation 1

Through field measurements along a survey line of 200 meters and by applying equation (2) to the separator systems (S1, S2, S3) in the upper parts, it was found out that the average values of (JS) reached 250 cm and with a classification of (Extremely widely spaced) Table 6. Thus, their joint spacing is in a large size, and this is what has been confirmed in the field. As for the lower parts, the average distance between the dividers (JS) was 56 cm and in general (Moderately wide spaced). Field evidence confirms that the lower part Parallel to the slopes separates into small parts and abounds in rock debris of various sizes. It should be noted here that the joint system is calculated for each system separately and then the general average of the studied outcrop is calculated. Furthermore, it is not possible to generalize about the same rock formation because the systems vary from site to site.

Table 6. Classification of the distance between joints [18]

Measurement (cm)	Descriptive Terms
200<	Extremely widely spaced
60 - 200	Widely spaced
20 - 60	Moderately widely spaced
6 - 20	Closely spaced
2 – 6	Very closely spaced
>2	Extremely closely spaced

Durability of Rock Mass (RQD): It is abbreviated as (RQD). Deere et al. (1967) developed Equation (3) to determine the durability of rock masses during the process of digging tunnels and building roads, i.e. taking field measurements based on core samples (CORE) [19].

$$\mathrm{RQD} = \frac{\sum Length\ of\ core\ pieces > 10cm}{Total\ length\ of\ core\ run} \times 100.\ \text{Equation (3)}$$

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The results obtained are described in Table 7 below. The question is “What would we do if the rock masses were at the top of the cliffs?” The answer is "Not accessible by drilling rigs". The first attempts to change the format of the equation were made by Palmstrom (1974), In 1982, Equation (4) was adopted for several considerations, including:

a. The readings and results provide a sufficient description of the durability of outcrops.
b. The results take into account the deepening of joints in the rock mass.
c. Equation (4) was developed to clarify the invisible cracks based on the size of the joints (Joints Volumetric).

$$RQD = 115 - 3.3(JV). \text{ Equation (4)}$$

Where
(JV) = the sum of the number of jointers per longitudinal unit for all joint groups. This property is characterized by the fact that its measurement depends on the number of joints measured in the field and within the area of the studied sector [20].

Table 7. Description of the durability of a rock mass [20]

Description of RQD %	Durability %
Very Good	90 – 100
Good	75 – 90
Fair	50 – 75
Poor	25 – 50
Very Poor	25<

JV is an indicator of how outcrops are likely to behave. This is because the mass size, shear strength and internal properties contribute to determining the mechanical performance of the rock mass [21]. (JV) values are calculated in two ways:

a. If there is one system (set), two, three or more systems, Equations (3-6) shall apply.

$$JV = \frac{1}{S1} + \frac{1}{S2} + \frac{1}{S3} + \frac{1}{SN} \dots. \text{Equation (5)}$$

where (S1, S2, S3) = average distance between jointers in each system

b. If there are more than one system (sets) with random cracks (NR), it is advisable to add the number of random cracks and the area of the sector (A) and Equation (6) is applied [22].

$$JV = 1/S1 + 1/S2 + 1/S3 + \cdots..1/SN + NR/5\sqrt{A} \text{ .... Equation (6)}$$

To assess the durability of rock masses, Equation 2, Equation 4, and Equation 5 were applied in the upper slopes, where random cracks were minimal. Measurements along a 100-meter scan line showed an RQD value of 44.05% poor, Table 7. In the lower slopes, with numerous random cracks, Equation 2, Equation 4 and Equation 6 were used, yielding an RQD value of 20% (very poor). The variation in durability is primarily influenced by the number of joint systems, their spacing, and the presence of random cracks.

Results & Discussion

Site (L1-R-R-21): Figure 3 illustrates part of the studied outcrop, where field visits identified disturbing samples prone to avalanche. The rocks belong to dolomite, and the parallel slopes are part of the excavations for the Al-Rujban mountain road, showing regularly cut rocks. The road lacks shoulders or trenches to contain avalanched sediments. Drainage streams are blocked by sediment, hindering water flow and pushing debris onto the road, which can obstruct traffic and cause vehicle skidding. Regarding weathering, several joint systems were observed, with random cracks indicating mechanical weathering, while chemical weathering was minimal, showing only narrow calcite deposits.
Three joint systems (S1, S2, S3) intersect at angles up to 90°, leading to the separation of rock masses. This increases the risk of large rock avalanches reaching the road, which is only two meters away. The joints, averaging 2.5 meters in length, are classified as medium-sized, with an average internal extension of 75 cm. The joints are filled with rock debris, often incoherent, indicating a lack of binding materials that could contribute to slope stability. The field study revealed that the main joints (S1, S3) function as waterways sloping toward the road, contributing to erosion, material removal, and rock debris avalanches, forming conical shapes with a stability angle of 45°.

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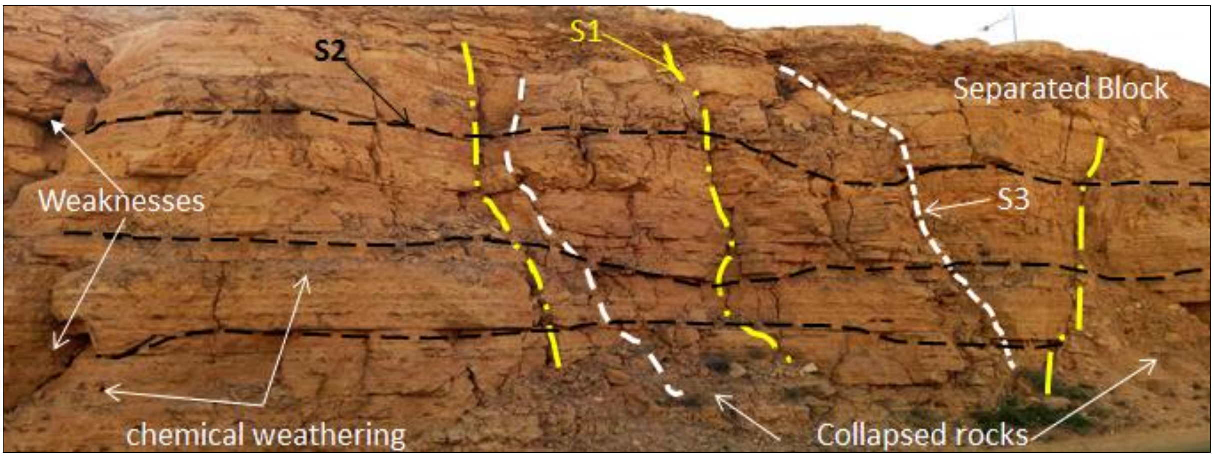

Figure 3. Outcrop Parallel in the site (L1-R-R-21).

The slopes alongside the road facilitate the transport of avalanched materials toward the road. Instead of falling directly, rock masses move toward the road due to the new slopes with cutting angles between 75˚ and 90˚, leading to rock falls. In the conical areas, the rock masses exhibit rolling and jumping behavior, as the rocks are hard. The geometric and mathematical analysis in table 8 showed that the joint separation is moderately narrow, with no binding materials, allowing smooth water flow. The joint spacing, with an average of 89.9 cm, is classified as widely spaced, contributing to an RQD of 44%, indicating a stable outcrop

Table 8. Results obtained from Site (L1-R-R-21).

Site area	300 m²
Roughness Type	Medium
Continuity	75 cm
Type of Movement	Rock Fill
Infilling Materials	Carbonate and Mud
Slope Angle	75˚-90˚ - Poor
RQD	44 %
Joint Spacing (JS)	89.9cm —Widely Spaced
Separation	60 – 200 mm—Moderately narrow

Site (L2-R-R-21): The site was characterized by the presence of dolomite limestone rocks. Field measurements show the presence of the intersection of two joint systems S2, S1. These joints are characterized by their convergence which leads to the separation of the rock masses that make up the slope to small sizes. Because the intersection of the two systems was at an angle of about 90°, this stabilized those separated rock masses in place. As for the effect of the joints, it is limited to causing weakness and brittleness in the rocks of the slope unless a movement stimulator intervenes, which in turn will lead to the avalanche of rock fragments, which most likely will be debris of various sizes figure 4.

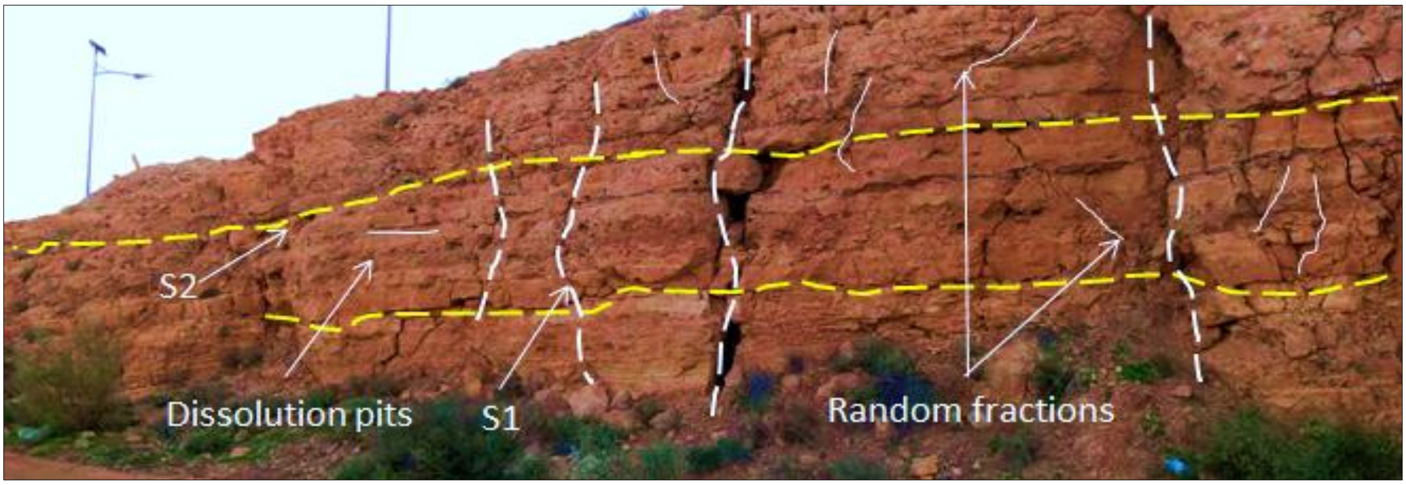

Figure 4. Outcrop Parallel in the Site (L2-R-R-21)

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As illustrated by table 9 below, there are no shoulders or trenches where any avalanched sediments piled up. Practically, this is considered a weakness of the road. Fragments and debris will reach the road directly in the case of collapse, resulting in damage to road users. As for the effect of chemical weathering, it emerged in the melting pits (dug by using melting drilling), although their spread is small, but they are more present Site (L2-R-R-21) due to the change in the rock characteristics, that is, the high percentage of calcium, which is one of the basic components of limestone. The effect of mechanical weathering is seen in the rocks of the slope. The most prominent features of this effect are random joints and cracks, the latter lacking in the site (L1-R-R-21). The most important movement expected to take place is rock fall because the cutting angle is 90°. As for the size and extension of the joints, they averaged 2.5 meters to be classified as medium length, and thus did not differ from Site (L1-R-R-21).
According to the results obtained from the study of geometric properties and the mathematical analysis of geometric properties, separation was classified as very narrow with an average value of 20 mm. The Joint Spacing system has a value of 19 cm and generally described as Closely Spaced. The RQD is rating of 20%, as the outcrop is in a state of general weakness, but its separated rocks still settle in place, unless this balance was affected by a movement stimulus.

Table 9. Results obtained from Site (L2-R-R-21)

Site area	**300 m²**
Roughness Type	Rough
Continuity	10 cm
Infilling Materials	Carbonate & Mud
Slope Angle	90˚
Type of Movement	Rock Fill & Debris
RQD	20% —Very Poor
Joint Spacing (JS)	19 cm — Closely Spaced
Separation	20 mm—Very narrow

Upon examining figure 2, it is evident that the joint system S1 passes through both sites. This suggests that the joints formed after the deposition of carbonate rocks. Additionally, their internal extension lies beneath the roads, presenting an invisible hazard. These joints create weak zones that contribute to the collapse of the rock masses supporting the road, leading to subsidence and potential road damage.

Conclusion

The study revealed that the rocks forming the slopes adjacent to the road belong to the Nalut Formation and primarily consist of dolomite and dolomitic limestone. It was found that the adjacent rocks were cut at a 90° angle for road construction purposes. The results indicate that dolomite rocks, located in the upper parts of the slopes, are less susceptible to chemical weathering, whereas limestone rocks in the lower parts exhibit both chemical and mechanical weathering, leading to the formation of cracks and joints. Measurements and data analysis showed high rock durability values (RQD) for dolomite rocks due to the increased spacing between joints, which reduces separation values and enhances slope stability unless affected by triggering factors. Rainfall was identified as a key factor contributing to rock erosion and movement initiation. Given the potential hazards to the road, the study recommends the removal of collapsed or at-risk rock masses to mitigate dangers for road users. Additionally, continuous monitoring of the road and its slopes is crucial for detecting any changes that might impact stability, ensuring road sustainability and user safety.

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المستخلص

تتأثر المنحدرات الموازية للطرق الجبلية بالعوامل الطبيعية والبشرية كعمليات قطع المنحدرات أثناء إنشاء الطرق، مما يجعل تقييم استقرار المنحدرات أمرًا ضروريًا، تساهم عوامل مثل هطول الأمطار والزوايا غير المناسبة لقطع الصخور في حدوث ضعف المنحدرات وحدوث الانهيارات الصخرية، مما يسبب أضرارًا للطرق ويشكل خطرًا على مستخدميها. يهدف هذا البحث إلى تقييم استقرار مكاشف تكوين نالوت على طول للطريق الجبلي الرجبان؛ تم إجراء دراسة ميدانية، حيث تم ترميز الموقع بـــ (L-R-R-21) واختيار موقعين (L1- L2) بهدف جمع العينات وإجراء القياسات المتعلقة بالشقوق والفواصل ودراسة خصائص الكتل الصخرية، بما في ذلك مؤشر متانة الصخور(RQD)؛ أظهرت النتائج أن الموقع L1 يحتوي على ثلاثة أنظمة للفواصل الصخرية(S1 ، S2، S3)حيث تتقاطع الفواصل S1 و S2 بزاوية 90°، مما أدى إلى انخفاض قيمة RQD إلى 44%، وصُنّفت على أنها "ضعيفة". كما أشار نظام الفواصل إلى وجود تباعد كبير بين الكتل الصخرية، حيث تم قياس متوسط المسافة بين الفواصل (JS) بـــ 89 سم، مما يصنّفها ضمن الفواصل المتباعدة بشكل كبير. وأدى قطع المنحدرات بزاوية 90° إلى حدوث انهيارات صخرية. أما الصخور في الجزء السفلي من التكوين فكانت أصغر حجمًا بسبب كثرة التشققات العشوائية، في حين كانت الصخور في الجزء العلوي من التكوين أكبر حجمًا وأكثر خطورة في حال انهيارها، وتوصي الدراسة بإزالة الكتل الصخرية المنهارة نظرًا لخطرها، ومراقبة الطريق ومنحدراته بشكل دوري للكشف عن أي تغيرات قد تؤثر على استقراره، مما يساهم في ضمان استدامة الطريق وسلامة مستخدميه.

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