



Study and Assessment of Ground Failures and Landslides Along the Mountain Roads in the Al-Hamra and Al-Labib Areas of the Western Mountain, Libya

دراسة وتقييم الانهيارات والانزلاقات الأرضية على طول الطريق الجبلية في مناطق الحمراء واللّبيب
بالجبل الغربي

Abdulhamed M. Salama¹, Abdulrouf A. Algraywe², Adel M. Elkrri³

أ. عبدالحميد مسعود سلامة* م. عبدالرؤوف عبدالهادي القريوي د. عادل محمد الكري

¹Geology Dept. Zentan University, Zentan, Libya

الجيولوجيا ، كلية العلوم ، جامعة الزنتان ، ليبيا

Abdulhamed.salama@uoz.edu.ly

²Geological Engineering Dept. Zentan University, Zentan, Libya

الهندسة الجيولوجية ، كلية الهندسة ، جامعة الزنتان ، ليبيا

Algrawe95@gmail.com

³Geology Dept. Zentan University, Zentan, Libya

الجيولوجيا ، كلية العلوم ، جامعة الزنتان ، ليبيا

adelelkrri@uoz.edu.ly

ABSTRACT

Landslides are among the common engineering problems, particularly in mountainous slopes and mountain roads. These natural hazards may cause significant material losses and, in some cases, human casualties due to the damage and erosion of roads, as well as the destruction and displacement of civil structures located near the affected areas. This study was conducted on the roads leading down the mountain in the Al-Hamra and Al-Labib areas of the Western Mountain (Jabal Al-Gharbi), with the aim of identifying the types of landslides and slope failures occurring in the study areas, determining the factors responsible for their occurrence, and identifying the types of forces acting on areas susceptible to landslides. In addition, nine rock samples were collected from the study areas to determine some of the petrophysical properties of the rocks, including porosity and permeability.



The results obtained revealed the occurrence of several types of landslides and slope failures in both study areas, including flow, slide, rock fall, and subsidence. The results also indicated that these phenomena mainly occur within rock formations characterized by high porosity and permeability values, with porosity exceeding 90% in all samples collected from the two study areas. These findings indicate a clear relationship between the petrophysical properties of the rocks and the susceptibility of the studied areas to landslides and slope failures.

الملخص .

تُعدّ الانزلاقات الأرضية من المشكلات الهندسية الشائعة، ولا سيما في مناطق سفوح الجبال والطرق الجبلية، حيث قد تسبب هذه الظواهر الطبيعية في خسائر مادية كبيرة، وأحياناً بشرية، نتيجة ما تُحدثه من أضرار وانجرافات للطرق، فضلاً عن تدمير وانجراف بعض المنشآت المدنية القريبة من مواقع حدوثها. أُجريت هذه الدراسة على الطرق المؤدية إلى أسفل الجبل في منطقتي الحمراء والليبب بالجبل الغربي، بهدف تحديد أنواع الانزلاقات والانهيارات الأرضية في مناطق الدراسة، والتعرف على العوامل المسببة لها، بالإضافة إلى تحديد نوع القوى المؤثرة في المناطق المعرضة للانزلاقات الأرضية. كما تم جمع تسع عينات صخرية من مناطق الدراسة بهدف قياس بعض الخصائص البتروفيزيائية للصخور، مثل المسامية والنفاذية. أظهرت النتائج المتحصل عليها وجود عدة أنواع من الانزلاقات والانهيارات الأرضية في كلتا المنطقتين، تمثلت في التدفق (Flow)، والانزلاق (Slide)، وتساقط الصخور (Rock Fall)، بالإضافة إلى الانخساف (Subsidence). كما أظهرت النتائج أن هذه الظواهر تحدث بصورة رئيسية ضمن تكوينات صخرية تتميز بارتفاع قيم المسامية والنفاذية، حيث بلغت نسبة المسامية أكثر من 90% في جميع العينات التي تم جمعها من منطقتي الدراسة. وتشير هذه النتائج إلى وجود علاقة واضحة بين الخصائص البتروفيزيائية للصخور وقابلية المناطق لحدوث الانزلاقات والانهيارات الأرضية.

Received: 26-07-2026

Accepted: 18-08-2026

Published: 02-09-2026

Keywords: Western Mountain, Al-Labib, Al-Hamra Area, Ground Failures, Landslides

الكلمات المفتاحية: الجبل الغربي، الليبب، منطقة الحمراء، الانهيارات، الانزلاقات

1. Introduction

Landslides are natural phenomena that represent a significant environmental and engineering hazard. They commonly occur on slopes and mountain hillsides when a combination of triggering and predisposing factors is present Terzaghi (1950). Landslides may occur suddenly, develop gradually in stages, or recur at widely



separated time intervals, depending on the nature of the influencing factors and the characteristics of the materials and rocks forming the slopes Highland & Bobrowsky (2008). Due to the significant damage that landslides may cause to roads, infrastructure, and civil structures, as well as their potential economic and human losses, this phenomenon has received increasing attention in many countries worldwide. This attention has included detailed investigations and monitoring of landslide-prone areas in order to understand their mechanisms and develop appropriate measures to reduce their risks. Effective management of landslide hazards requires an understanding of their nature and mechanisms, the identification of areas most susceptible to landsliding, and the determination of the factors and conditions that contribute to their occurrence. Such knowledge can contribute to reducing the impacts of landslides and minimizing the resulting material and human losses. Landslides can be classified into several types based on the nature of material movement and the type of material involved, whether soil, unconsolidated sediments, rock, or a combination of these materials. The movement may take different forms, including flow, slide, rock fall, and subsidence Hungr et al. (2014). The type of movement depends on several factors, including the nature and degree of cohesion of the geological materials, slope morphology and angle, hydrological conditions, and the structural characteristics of the rocks Highland & Bobrowsky (2008).

Several factors influence the occurrence of landslides. One of the most important is an increase in the water content of soils and rocks resulting from heavy rainfall or the melting of large amounts of snow and ice. This may increase pore-water pressure and reduce the shear strength of the affected materials Iverson (2000). Earthquakes are also important triggering factors that may initiate the movement of earth masses or reactivate pre-existing landslides. In addition, the removal or erosion of geological layers and materials that

provide support to slopes, whether as a result of natural processes or human activities, may lead to slope instability. The geological and structural characteristics of an area play an important role in determining the susceptibility of slopes to landsliding. For example, the likelihood of landslides may increase when rock strata are steeply inclined and their dip direction is consistent with the slope direction. Similarly, joints and fractures may promote instability when their orientations facilitate the movement of rock masses. Geological structures that are parallel to the sides of deep rivers and valleys may also increase the susceptibility of slopes to failures





and landslides. Gravity represents the fundamental driving force behind these phenomena, acting to move soil, sediment, and rock masses downslope, particularly when other contributing factors are present Highland & Bobrowsky (2008). In Libya, landslide problems are particularly evident in some mountainous regions, especially in the Green Mountain and Western Mountain areas, where steep and potentially unstable slopes are widespread. The likelihood of landslides increases in slopes characterized by faulted or fractured geological conditions, as well as in slopes that have been modified or cut during road construction through mountainous areas Alfandi & Meeloud (2023). Such activities may alter the natural equilibrium of slopes and increase their susceptibility to failure. Given the limited number of specialized studies addressing landslides in some mountainous areas of Libya, and the environmental and engineering challenges posed by these phenomena, which require further investigation and attention, the Al-Hamra and Al-Labib areas in the Western Mountain were selected for this study. The study aims to identify the types of landslides and slope failures occurring in the two areas, determine the factors influencing their occurrence, and investigate selected petrophysical properties of the rocks associated with these phenomena. The study is intended to contribute to a better understanding of the mechanisms responsible for landsliding, identify areas that are more susceptible to such hazards, and provide a scientific basis for reducing their risks and impacts.

2. Research Problem

Given the frequent occurrence of environmental problems associated with landslides and ground failures of various types along the edges of mountainous roads leading toward the coast in the Western Mountain (Al-Jabal Al-Gharbi) region, and the material and human losses resulting from these incidents, there is a need to investigate these phenomena and identify their nature, mechanisms of occurrence, and influencing factors. The research problem also involves identifying the areas most susceptible to landslides and ground failures, which will contribute to assessing their degree of hazard, reducing their impacts, and implementing appropriate measures to minimize potential risks to roads, infrastructure, and the lives of road users.

3. Research Statement

The study adopted a field-based approach involving several field visits to the selected study areas to collect the necessary data and assess the geological and environmental conditions associated with landslides



and ground failures. The fieldwork focused on identifying and classifying the observed ground phenomena, locating affected sites, and evaluating their surrounding areas, particularly their relationship with surface-water drainage and rainfall accumulation. Rock samples were collected from selected sites for laboratory analysis of relevant petrophysical properties. In

addition, the study sites were documented through field photographs, with particular emphasis on recording the locations, characteristics, and field manifestations of landslides and ground failures.

4. Geology and Geological Formations of the Study Area

The Western Mountain figure (1), also known as Jabal Nafusa, is a mountainous rocky range located in northwestern Libya. It extends from the Tunisian border in the west through the areas of Nalut and Gharyan toward Al-Khoms in the east, reaching a maximum elevation of approximately 968 m. The mountain range consists of a succession of geological formations representing different geological ages and depositional environments El-Zouki (1980). The following is a brief description of the main formations relevant to the study area.



Figure (1): A photograph taken from the upper part of the Western Mountain highlands.





1.1. Kursh Formation

The Kursh Formation is one of the older formations in the region and is generally assigned to the Early Triassic. It is mainly composed of clay with pale-white coloration, fine texture, and good sorting. Glauconite occurs as a light-green mineral, while other components include quartz, mica, and iron and manganese oxides El-Hinnawy & Cheshitev (1975). Cross-bedding structures are also observed within the formation. The sediments were deposited in a marine environment, while the upper part of the formation contains carbonate materials. The formation crops out at Kursh Dome, Ras Al-Mazoul Dome, Abu Rashada Dome, and Gharyan Dome. It extends westward into Tunisia and southward toward the Ghadames Basin, with a thickness of up to approximately 150 m.

1.2. Aboshaba Formation

The Aboshaba Formation overlies the Aziziyah Formation and extends across Jabal Nafusa toward the Ghadames and Jafara basins. It is predominantly composed of yellow to reddish sandstone, with the red coloration mainly attributed to hematite. Quartz is the dominant mineral, and the sandstone is generally characterized by high purity, medium-sized grains, and a relatively coarse texture. Breccia is also present and may have potential applications as a construction material. The formation is generally well sorted and contains a relatively low proportion of clay and fine-grained materials El-Hinnawy & Cheshitev (1975).

The formation was deposited mainly in a fluvial environment and displays prominent cross-bedding. Paleocurrent indicators suggest flow directions generally ranging from northwest to southeast and from southwest to northeast El-Zouki (1980). The formation is assigned to the Late Triassic and is generally characterized by a lack of fossils. It can be divided into lower and upper parts. The lower part is exposed around Abu Kamash and Sabratha and reaches approximately 80–120 m in thickness at Abu Ghailan. The upper part consists mainly of red and green clay with white lenses and includes coarse-grained structures within finer sediments. Carbonate content increases upward, and the depositional environment is interpreted as a meandering fluvial system El-Zouki (1980).

1.3. Abogaylan Formation



The Abogaylan Formation contains igneous dikes that cut the older geological units, indicating that these intrusions are younger than the rocks they penetrate and therefore provide evidence for relative age relationships. The dikes are composed mainly of intermediate igneous rocks. The formation also contains green and red clay, with the green coloration reflecting relatively oxidizing conditions, while the red coloration is mainly associated with hematite.

The formation forms a transitional interval between the Abogaylan and Aboshaba formations, with relatively gradual contacts in some areas. Ripple marks and breccia are also observed. The depositional environment has been interpreted as transitional, including lacustrine and sabkha settings. The formation is generally assigned to the Early Jurassic and contains fossil remains. Its thickness is approximately 80 m Muftah & El-Zouki (2021).

1.4. Kakla Formation

The Kakla Formation overlies the Abogaylan Formation with an unconformable contact. It is mainly composed of fine-grained mudstone and sandstone, with reddish coloration resulting from iron oxides. Sedimentary channels and depositional structures are common, and conglomeratic beds occur above sandstone and clay-rich intervals El-Zouki (1980). The formation was deposited primarily in a fluvial environment and locally grades upward or laterally into limestone. It becomes thinner toward the east and disappears near Wadi Ghan Dam, whereas westward it extends toward Tunisia, where its thickness ranges between approximately 30 and 60 m. Fossils, including remains of petrified trees, have been reported. Parallel and cross-bedding structures are also present Muftah & El-Zouki (2021).

1.5. Sidy Alsiad Formation

The Sidy Alsiad Formation is divided into two main members: the Ain Tabi Member and the Yefren Member. Dolomitic limestone is the dominant lithology. The Ain Tabi Member contains igneous intrusions and fossil remains, including shell-bearing fossils and bivalves. It was deposited in a relatively deep-marine environment and is generally assigned to the Late Cretaceous El-Hinnawy & Cheshitev.

The Yefren Member is characterized by multicolored marl, including yellow, green, brown, and gray varieties, with interbeds of shale, limestone, dolomite, and gypsum. It is also assigned to the Late Cretaceous and represents a transitional depositional environment ranging from coastal lagoons to marine settings.



1.6. Nalut Formation

The Nalut Formation occurs above the Yefren Member and is mainly composed of chert and dolomite. It is assigned to the Cretaceous and extends from the Gharyan area eastward to Tunisia in the west, with a regional extension toward the Ghadames Basin. Its thickness ranges from approximately 30–35 m in the Nalut area to about 35–60 m around Gharyan El-Zouki (1980). The contacts between the underlying units are generally conformable, and the formation is interpreted to have been deposited in a relatively deep-marine environment. In some areas toward Al-Khoms, its thickness may reach approximately 200 m El-Hinnawy & Cheshitev (1975).

1.7. Qaser Tigrana Formation

The Qaser Tigrana Formation is predominantly composed of marly limestone, commonly characterized by pink to reddish coloration and containing abundant fossil remains, particularly molluscan fossils El-Zouki (1980). The formation extends from the Bani Walid area in the east toward Tunisia in the west and extends southward toward Qaryat and Al-Shwerif. Toward the Mizda area, the formation locally undergoes facies changes associated with evaporitic deposits Muftah & El-Zouki (2021).

The formation represents a marine to marginal-marine depositional environment, including shallow lagoons and coastal ponds. Its thickness is approximately 85–90 m, reaching about 130 m in the Mizda area, while the thickness of the Qaser Tigrana interval itself may be approximately 70 m. In the western part of the Hamada Al-Hamra, thicknesses of about 45–68 m have been reported Shalaby (2025).

1.8. Bir Al-Ghanem Formation

The Bir Al-Ghanem Formation is dominated by gypsum with subordinate dolomite. Gypsum is composed mainly of calcium sulfate ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) and commonly occurs as a prominent marker bed within the geological succession. The formation may also function as a cap-rock unit and is characterized by evaporitic features and structures associated with restricted depositional conditions El-Zouki (1980).

The formation is interpreted to have developed in a restricted evaporitic marine basin where extensive evaporation promoted the precipitation of evaporite minerals. It extends from the Rabta area eastward toward the Ghadames Basin and westward toward Tunisia. The formation may reach approximately 400 m in thickness and is considered broadly contemporaneous with the Abogaylan Formation El-Hinnawy & Cheshitev (1975).



The Qasir Beniran Formation follows the Bir Al-Ghanem Formation and is mainly composed of dolomite, which is interpreted to have formed largely through diagenetic processes. The formation is relatively thin, with a thickness of approximately 20 m, and its clay content generally increases upward. The formation is clearly recognized in parts of the Ghadames and Murzuq basins, whereas its occurrence is less clearly defined in the Gharyan area. Its lower part is associated with shallow-marine or lagoonal conditions, while the upper part reflects a transition toward deeper-marine depositional conditions Anketell & Ghellali (1983).

1.9. Tikbal Formation

The Tikbal Formation consists mainly of limestone and dolomite and is generally assigned to the Middle Jurassic. It is absent from parts of the eastern Jabal Nafusa because of erosion that occurred during a later geological period. The formation can serve as a useful stratigraphic marker and extends from Yefren westward toward Tunisia and southward toward the Ghadames Basin Anketell & Ghellali (1983).

The formation contains abundant microfossils and macrofossils, including foraminiferal assemblages. Its maximum thickness is approximately 50 m. The depositional environment is interpreted as ranging from coastal to marine conditions Anketell & Ghellali (1983).

4.10. Khashem Al-Zarzour Formation

The Khashem Al-Zarzour Formation is predominantly composed of sandstone and is assigned to the Jurassic. It is characterized by prominent cross-bedding structures, which are interpreted to reflect changes or reversals in current directions El-Hinnawy & Cheshitev. The formation consists of two main members. The lower member, known as the Al-Joush Member, is characterized mainly by green clay, whereas the upper member consists predominantly of sandstone and is assigned to the Middle to Upper Jurassic Shalaby (2025).

The upper member reaches a thickness of approximately 90 m and is separated locally by an unconformity. The sedimentary structures and grain characteristics suggest significant aeolian influence in parts of the depositional system Muftah & El-Zouki (2021).

4.11. Shakshouk Formation

The Shakshouk Formation occurs above the Khashem Al-Zarzour Formation and consists mainly of alternating sandstone and clay-rich sediments El-Hinnawy & Cheshitev (1975). It is assigned to the Late Jurassic



and represents a relatively shallow-marine to coastal depositional environment Muftah & El-Zouki (2021). The formation displays cross-bedding structures, including forms related to changing current directions, and is generally characterized by medium-sized grains. A gradual vertical change in lithology is observed, with carbonate-rich deposits occurring toward the lower part and sandstone becoming more dominant toward the upper part Anketell & Ghellali (1983).

5. Methodology

The methodology adopted in this study was based primarily on field investigations and laboratory tests. Several field visits were conducted to the study areas to identify the types of ground failures present, determine whether the sites were affected by landslides, ground collapses, or both, and locate the most significant sites. The surrounding conditions of the identified sites were also investigated, with particular emphasis on their relationship to surface-water drainage pathways and areas of rainfall accumulation. Photographic documentation was carried out at the study sites, particularly at locations affected by landslides and ground failures.

In addition, representative rock samples were collected from the selected sites for laboratory analysis. The porosity and permeability of the samples were determined because these petrophysical properties are important parameters for evaluating the hydrogeological and geotechnical conditions that may influence the occurrence and development of landslides.

5.1. permeability Test.

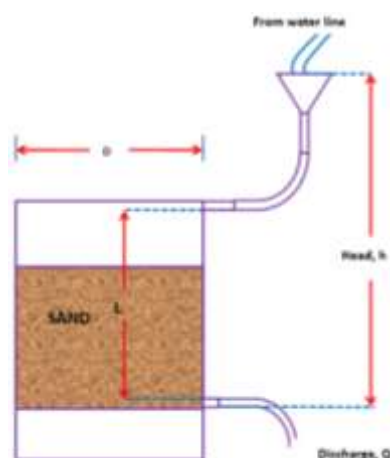


Figure (2): Shows the basic parts of the apparatus used to measure permeability.



The permeability of the collected samples was determined using the constant-head permeability test, which is commonly used to determine the hydraulic conductivity of relatively coarse-grained materials such as sand and gravel. The principle of the constant-head test is based on allowing water to flow through a prepared sample under a constant hydraulic head difference between the inlet and outlet. The volume of water passing through the sample during a known period of time is measured, and the hydraulic conductivity of the sample is subsequently calculated figure (2) Fredlund & Rahardjo (1993).

The main components of the apparatus were as follows:

1. A constant-head reservoir.
2. An open-ended cylindrical sample container, approximately 15 cm in height and 6 cm in diameter.
3. A graduated container for collecting the discharged water.
4. A stopwatch.
5. A thermometer.
6. A sensitive balance.

The apparatus used in this study was designed by the researcher according to the basic specifications and operating principle of the standard constant-head permeability test. Since the required laboratory apparatus was not available in the university laboratories, locally available and conventional materials were used to construct a simple experimental setup suitable for conducting the test. The apparatus and equipment used by the researcher to determine the permeability of the samples collected from the study areas are presented in figure (3.2 a, b, and c).

Procedures

1. The permeability test was conducted according to the following procedures:
2. The sample was prepared either by inserting the cylindrical container directly into the material at the selected site to obtain an undisturbed representative sample, or by collecting a disturbed sample and placing it inside the cylinder and compacting it appropriately.



Figure (3 - A, B, C): Shows the equipment and tools used by the researcher to estimate permeability.

1. The lower end of the sample container was covered with a piece of suitable filter cloth or No. 200 sieve mesh to prevent the loss of fine particles while allowing water to pass freely through the sample.
2. The sample cylinder was placed inside the main reservoir of the apparatus and covered from above with a lid containing an opening through which water could enter.
3. The upper reservoir was completely filled with water. A constant hydraulic head difference between the water level at the inlet and the outlet was maintained by opening a valve that allowed excess water to discharge from the system.



Water was allowed to flow through the sample. At the same time, the stopwatch was started, and a known volume of water (Q) was collected over a measured period of time (t). The temperature of the water was also measured. The hydraulic conductivity (permeability coefficient) was calculated using the following relationship:

$$K = QL / Aht$$

Where:

- **K = hydraulic conductivity (permeability coefficient).**
- **Q = volume of water collected during the test (cm³).**
- **L = length of the sample (cm).**
- **A = cross-sectional area of the sample perpendicular to the direction of water flow (cm²).**
- **h = constant hydraulic head difference (cm).**
- **t = time required to collect the measured volume of water (s).**

When calculating permeability at a temperature of 20°C, the following equation is used:

-where μ represents the viscosity of water.

5.2. Porosity Test

Porosity was determined using a volumetric method based on measuring the volume of water required to fill the pore spaces within a known volume of dry sample.

The principle of the method is based on determining the volume of the pore spaces by comparing the known total volume of the sample with the volume occupied by the solid material. The difference between these two volumes represents the pore volume. The porosity is then expressed as the ratio of pore volume to total sample volume, multiplied by 100 Marin & Velásquez (2020).

Equipment Used

Because specialized laboratory equipment was not available, the experimental equipment was manually prepared by the researcher using commonly available materials and tools, while maintaining the basic requirements of the standard volumetric method.

The equipment used included:



1. A 250-mL volumetric flask.
2. A 50-mL graduated cylinder.
3. Water.
4. A sensitive balance.
5. A suitable measuring container for collecting and measuring the samples.

The equipment used in the experiment is presented in Figure (4 - a, b, and c).



Figure (4 - A, B, C): Shows the equipment used to measure the porosity of the samples collected from the study area.

Procedures

The porosity test was performed according to the following procedures:

1. A representative sample was collected using a container of known volume. For example, the initial volume of the sample was 25 cm³.



2. The sample was weighed in its dry condition. For example, a dry sample with a volume of 25 cm^3 had a mass of 38.66 g.
3. The dry sample was transferred into the volumetric flask, and water was gradually added until the required reference mark was reached.
4. The volume of water added was measured using the graduated cylinder.
5. The volume of the solid portion of the sample was calculated from the difference between the known total sample volume and the volume of the pore spaces.

The calculations were performed as follows:

Volume of solid material = Total sample volume – Pore volume

Pore volume = Total sample volume – Volume of solid material

The percentage porosity of the sample was calculated using the following equation:

Porosity (%) = (Pore volume / Total sample volume) $\times$ 100.

The calculated porosity values were subsequently used, together with the permeability results and field observations, to assess the physical characteristics of the rocks and their possible relationship to the occurrence and development of landslides in the study areas.

6. Discussion and Result

6.1. Interpretation of the Porosity and Permeability Results of the Studied Samples

A total of nine rock samples were collected from the study areas, as shown in figure (5 – 1.2.3.4.5.6.7.8.9), and were assigned the corresponding sample numbers. The porosity and hydraulic conductivity (permeability) of the collected samples were determined using the appropriate equations.

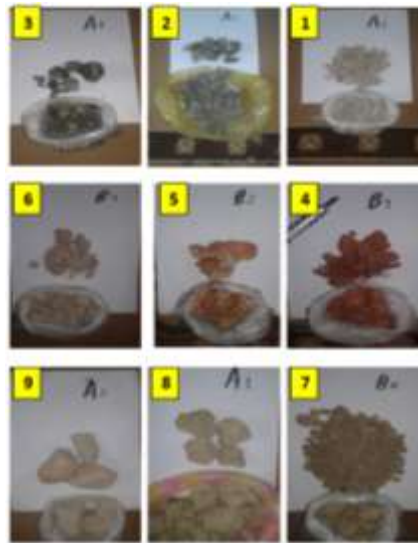


Figure (5): Nine samples (1, 2, 3, 4, 5, 6, 7, 8, and 9) collected from the study areas.

The results indicated relatively high values for the measured properties, with the reported values exceeding 90%. These results suggest that the geological formations exposed within the study areas possess physical characteristics that may contribute to their susceptibility to water infiltration and, consequently, to the development of landslides and ground failures. The porosity and permeability results are presented in Tables (1) and (2), respectively. These tables also demonstrate the application of the relevant equations and the calculated values obtained for the studied samples.

It should be noted that the high porosity and permeability values should be considered together with the field observations, geological characteristics, slope angle, rainfall, surface-water drainage, and degree of weathering when evaluating the susceptibility of the study areas to landslides and ground failures.



N. Sample	Measured Volumes	Porosity Calculation Equation	Results
1	Dry sample weight: (200 g) Water volume: (200 mL) Void volume: (180 mL)	Porosity = (Volume of Voids / Total Volume of Sample) × 100 Porosity = (180 / 200) × 100 = 90%	90%
2	Dry sample weight: (200 g) Water volume: (200 mL) Void volume: (190 mL)	Porosity = (Volume of Voids / Total Volume of Sample) × 100 Porosity = (190 / 200) × 100 = 95%	95%
3	Dry sample weight: (200 g) Water volume: (200 mL) Void volume: (185 mL)	Porosity = (Volume of Voids / Total Volume of Sample) × 100 Porosity = (185 / 200) × 100 = 92.5%	92.5%
4	Dry sample weight: (200 g) Water volume: (200 mL) Void volume: (180 mL)	Porosity = (Volume of Voids / Total Volume of Sample) × 100 Porosity = (180 / 200) × 100 = 90%	90%
5	Dry sample weight: (200 g) Water volume: (200 mL) Void volume: (190 mL)	Porosity = (Volume of Voids / Total Volume of Sample) × 100 Porosity = (190 / 200) × 100 = 95%	95%
6	Dry sample weight: (200 g) Water volume: (200 mL) Void volume: (180 mL)	Porosity = (Volume of Voids / Total Volume of Sample) × 100 Porosity = (180 / 200) × 100 = 90%	90%

Table (1): Presents the porosity results and the method used to calculate them using the equation.

N. Sample	Sample Data	Permeability Calculation Equation	Results
1	Q = 100 mL L = 5 cm A = 75 CM 3 h = 30 cm t = 9480 s	$K = \frac{QL}{AhL} = \frac{100 \times 5}{75 \times 30 \times 9480}$	2.34×10^{-5}
2	Q = 80 mL L = 5 cm A = 75 CM 3 h = 30 cm t = 9480 s	$K = \frac{QL}{AhL} = \frac{100 \times 5}{75 \times 30 \times 9480}$	2.34×10^{-5}
3	Q = 100 mL L = 5 cm A = 75 CM 3 h = 30 cm t = 1800 s	$K = \frac{QL}{AhL} = \frac{80 \times 5}{75 \times 30 \times 1800}$	9.87×10^{-4}
4	Q = 55 mL L = 5 cm A = 75 CM 3 h = 30 cm t = 9480 s	$K = \frac{QL}{AhL} = \frac{55 \times 5}{75 \times 30 \times 4980}$	9.87×10^{-5}
5	Q = 75 mL L = 5 cm A = 75 CM 3 h = 30 cm t = 9480 s	$K = \frac{QL}{AhL} = \frac{75 \times 5}{75 \times 30 \times 4080}$	4.084×10^{-5}
6	Q = 100 mL L = 5 cm A = 75 CM 3 h = 30 cm t = 9480 s	$K = \frac{QL}{AhL} = \frac{100 \times 5}{75 \times 30 \times 9480}$	2.34×10^{-5}

Table (2): Presents the permeability results and the method used to calculate them using the equation.



6.2. Identification and Evaluation of the Types of Ground Failures in the Study Areas

6.2.1. Al-Hamra Area

The Al-Hamra area is located northwest of Al-Qawasim City. A mountainous road connecting Al-Qawasim City with the areas of the inner mountain (Batin Al-Jabal) crosses the Al-Hamra area. During the design and construction of the road by previous road-construction companies, several road cuts were made along the road margins. These cuts exposed parts of the geological formations in the area. The area is affected by recurring landslide and ground-failure phenomena. A field investigation was therefore conducted to identify, examine, and evaluate the different types of landslides and ground failures observed along the road. The results of the field investigation are described and discussed below.

Site 1

Figure (6) shows an exposure of the Yefren Marl Member, which represents one of the members of the Sidi Al-Siad Formation. The member consists predominantly of multicolored marl, including dark-gray marl, as shown in figure (6 and 7). The marl is interbedded with layers of shale, limestone, and dolomite.



Figure (6): Shows a section of the first site, which is part of the Sidi Al-Siad Formation. This section represents the area preceding the part that was affected by a landslide.

This part of the exposure represents the initial stage of the ground failure, as it occurs immediately before the more pronounced zones affected by landsliding and ground collapse. A representative sample was collected from this location and assigned the code (1), as shown in **figure (5)**. In contrast, another exposed section of the Yefren Marl Member above the mountain road in the Al-Hamra area has undergone a **forward landslide**. As shown in **figure (7 c)**, soil material from the upper part of the formation has moved downward and accumulated in the lower part of the exposure, where a progressive increase in displaced material can be observed.

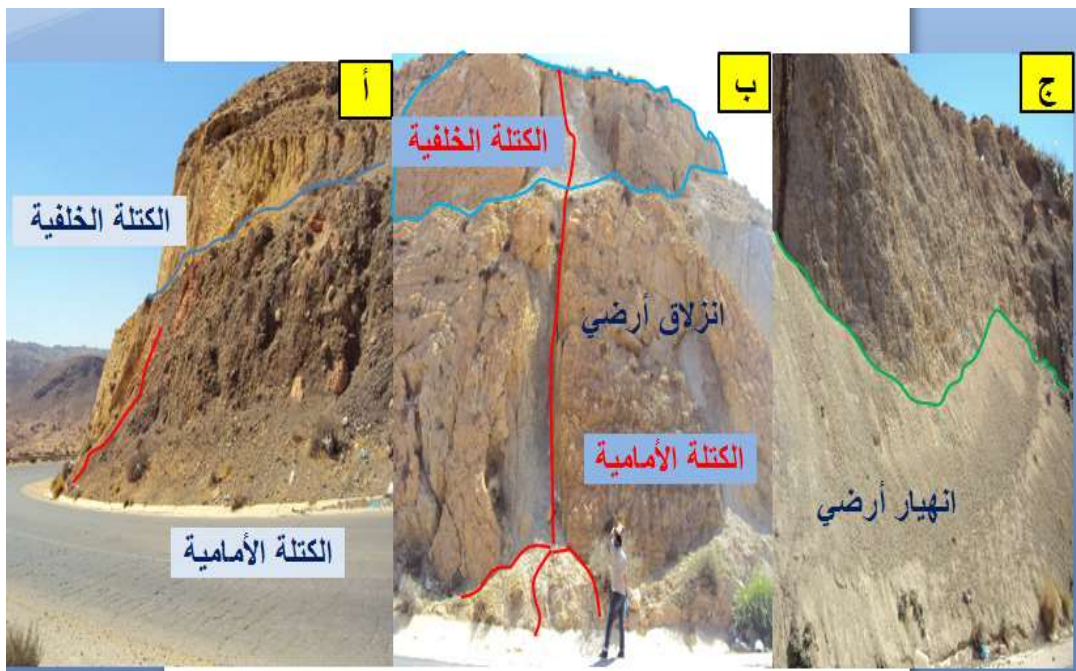


Figure (7): Shows the location of the ground failure and landslide that affected the upper part of the mountain road.

The middle section, represented by figure (7 b), has undergone failure accompanied by erosion and removal of part of the formation. The exposed material appears to be divided into two main portions: the rear portion representing the upper part of the section and the front portion representing the lower part. The failure has created a pathway through which rainwater runoff can flow across the middle part of the exposure, resulting in progressive erosion. Continued runoff and erosion may eventually contribute to the separation of the affected



section into two large blocks. Based on its observed characteristics and relatively rapid movement, this phenomenon is classified as a rapid landslide.

The third part of the member, located near a bend in the road, has undergone a gradual, slow-moving landslide. The affected section has separated into two blocks, consisting of an upper/rear block and a lower/front block,

as shown in figure (7 a). This type of movement is classified as a slow, progressive landslide. A representative sample was collected from this location and assigned the code (3), as shown in figure (5).

Site 2

The second investigated site in the Al-Hamra area is located near the lower end of the mountain road. The exposed section at this location represents part of the Kursh Formation. The formation is characterized mineralogically by the presence of feldspathic or other light-colored mineral components, including pink material speckled with white and reddish-brown material with white speckles, as observed in figure (7).

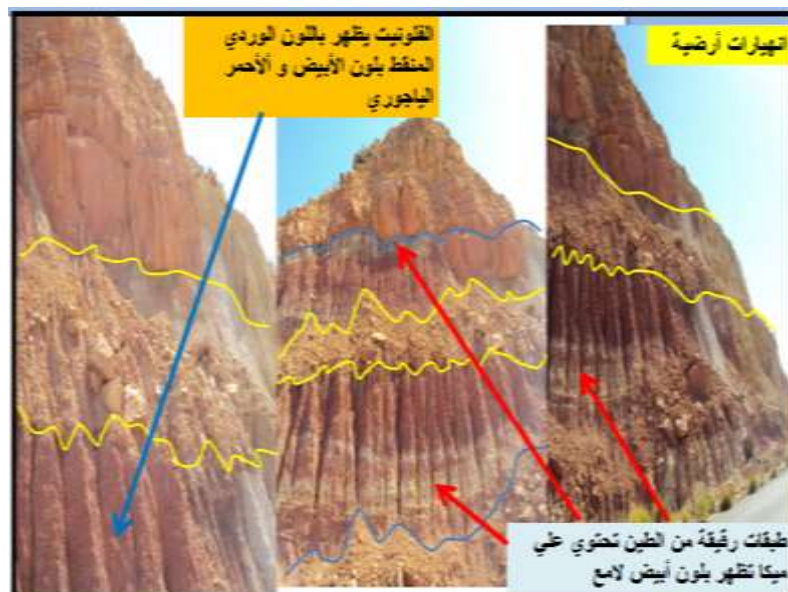


Figure (8): Shows the second site in the study area of Al-Hamra, located at the lower end of the mountain road, and illustrates the thin clay layers within the formation that contributed to the occurrence of the ground failure.

The exposure also contains thin clay-rich layers containing mica. The mica gives the clay a shiny appearance, while the clay itself is characterized by a pale-white color and fine texture. The presence of clay-rich layers within a steeply inclined geological section may reduce the shear resistance along the contact between the clay and the



overlying rock masses, thereby facilitating downslope movement under the influence of gravity. In addition, clay-rich layers can absorb and retain significant amounts of water. With increasing water saturation, the strength of the clay may decrease, potentially promoting sliding of the overlying rock masses along the clay-rich layer. A representative sample was collected from this site and assigned the sample codes (4, 5, 6, and 7), as shown in figure (5).

Another part of the site represents an exposed section of the Kursh Formation characterized by green-colored clay-rich material with a fine texture, interbedded with pink and reddish-brown material containing white speckles. The green coloration may reflect the mineralogical composition and depositional or post-depositional conditions of the sediments. The observed landslide also exhibits significant internal mixing of particles during movement. Material from

the upper part of the slide becomes incorporated into the lower part, while material from the lower part may also be displaced upward and mixed with the overlying material. This type of movement, characterized by considerable internal deformation and mixing of the displaced material, is classified as a flow-type landslide (flow), as illustrated in figure (9). A representative sample was collected from this location and assigned the sample codes (4, 6, and 7), as shown in figure (5).



Figure (9): Shows the flow-type landslides present at the second site in the Al-Hamra area, which occur as a result of the mixing of particles accompanied by movement.



6.2.2. Al-Labib Area

The Al-Labib area is located north of Al-Asabaa City. A mountainous road connecting the city with the areas of the inner mountain, beginning near the towns of Al-Rabta, crosses the Al-Labib area, as shown in figure (10). During the design and construction of the road, several road cuts were created along its margins. These cuts exposed parts of the geological formations and increased the visibility of the rock units in the area.



Figure (10): Shows the flow-type landslides present at the second site in the Al-Hamra area, which occur as a result of the mixing of particles accompanied by movement.

The area is affected by landslides and other forms of ground failure. A field investigation was conducted to identify and evaluate these phenomena and to determine their relationship with the geological and topographic conditions of the area. The results of the field investigation are presented below.

Site 1

This site is located within a relatively steeply inclined section of the mountain road, near the beginning of the first road bend. On the western side of the road, the outer layer of the exposed section has undergone surface failure, as shown in figure (11). The affected section represents the upper part of the Aboshaba Formation, which is characterized by relatively high porosity and permeability and may therefore possess favorable reservoir characteristics. During rainfall events, the upper part of the exposure may become saturated as a result of the accumulation and infiltration of rainwater. Because the section has a steep slope, increased water saturation may reduce the stability of the weathered or loosened surface material and contribute to its failure.



Figure (11): Shows the landslide at the first site in the Al-Labib area.

This phenomenon can therefore be classified as a rapid ground failure. The green and light-brown colors observed in the exposure are consistent with the occurrence of red and green clay-rich sediments within the upper part of the Aboshaba Formation. A representative sample was collected from this site and assigned the sample codes (8 and 9), as shown in figure (5).

Site 2





This site represents an exposed section of the Aboshaba Formation in the Al-Labib area. The exposure is characterized by a very steep slope, with an inclination exceeding approximately 80° . The Aboshaba Formation consists predominantly of sandstone characterized by relatively high porosity and permeability. At this site, the sandstone displays a yellow coloration with light reddish-brown staining, which is attributed to the presence of iron oxides, particularly hematite. A significant amount of breccia is also observed within the exposure. Coarse fragments occur within finer-grained rock material, producing a heterogeneous texture that may increase the effective pore space and permeability of parts of the section. Consequently, rainfall infiltration and water saturation may occur relatively rapidly. Under conditions of high water saturation and steep slope inclination, the stability of the exposed material may be reduced, resulting in sudden failure of the frontal part of the section.



Figure (12): Shows the second site in the Al-Labib area, illustrating the rapid ground failure caused by the steep slope.

The observed movement is interpreted as a subsidence-type ground failure, in which the displacement is predominantly vertical rather than parallel to the slope. Partial saturation of the formation may contribute to



the development of localized subsidence, as illustrated in figure (12). A representative sample was collected from this site and assigned the sample code (8), as shown in figure (5).

1. Conclusions

Based on the results obtained from the porosity and permeability tests, it was found that the landslides and ground failures observed in the two study areas are associated with geological formations characterized by relatively high porosity and permeability. The measured values exceeded 90% in all samples collected from the two study areas, according to the reported results. These properties may facilitate water infiltration and saturation and may consequently contribute to reducing the stability of slopes under favorable geological, hydrological, and topographic conditions.

In the first site in the Al-Hamra area, which represents the Yefren Marl Member of the Sidi Al-Siad Formation and contains interbeds of shale, limestone, and dolomite, the field observations indicate the development of an initial ground-failure zone. Other exposed parts of the Yefren Marl Member along the upper section of the mountain road experienced landsliding and ground failure across the exposed section. A portion of the formation became separated into front and rear blocks, and the observed movement was classified as a rapid landslide.

The third exposed part of the member, located near a road bend, experienced a gradual landslide, resulting in the separation of the affected section into two blocks: an upper/rear block and a lower/front block. Based on its field characteristics and observed rate of movement, this phenomenon was classified as a slow, progressive landslide.

The second site in the Al-Hamra area represents an exposure of the Kursh Formation, which contains thin, fine-grained, pale-colored clay layers. The presence of these clay-rich layers contributes to the susceptibility of the formation to water absorption. With increasing water saturation, the shear strength of the clay-rich material may decrease, potentially facilitating downslope movement of the overlying rock masses and promoting landslide development.

In another exposed section of the same formation, the observed landslide was characterized by substantial mixing and internal deformation of particles during movement, with material being displaced and incorporated



from the upper to the lower parts of the slide and vice versa. Based on these characteristics, the observed movement was classified as a flow-type landslide (flow).

In the Al-Labib area, landslides and ground failures were identified at two exposed sites within the Aboshaba Formation, a sandstone-dominated formation characterized by relatively high porosity and permeability and potentially favorable reservoir properties.

At the first site, surface failure followed by downslope movement was observed. The upper part of the exposure became saturated with rainfall, which contributed to the separation and subsequent gradual failure of part of the exposed material. Based on the observed behavior, this failure was classified as a rapid to moderately rapid movement.

At the second site, the ground failure occurred within a very steeply inclined section. The observed movement was classified as subsidence, characterized predominantly by vertical displacement along the exposed section. The combination of steep slope inclination, rainfall infiltration, and the physical properties of the sandstone may have contributed to the development of this type of ground failure.

Overall, the field observations indicate that the occurrence and development of landslides and ground failures in the study areas are controlled by the interaction of several factors, including lithology, porosity and permeability, slope inclination, rainfall infiltration, surface-water drainage, and the degree of weathering and fracturing of the exposed formations.

2. Recommendations

Based on the evaluation of the landslides and ground failures identified in the study areas, the following recommendations are proposed for consideration by the relevant authorities and road-management agencies:

1. Installation of protective wire meshes and rockfall barriers:

Protective wire meshes and suitable rockfall-control systems should be installed on exposed sections that have experienced landslides or ground failures, particularly in areas with moderate or gradual slopes. Such measures can improve the stability of the exposed surface and reduce the movement and downslope rolling of loose rock fragments and blocks onto the roadway under the influence of gravity.

2. Construction of reinforced concrete protection structures:



Appropriate reinforced-concrete retaining or protective structures should be considered at the upper and/or vulnerable parts of exposed sections affected by flow-type landslides and in the vicinity of very steep slopes. These areas may be susceptible to sudden failure, which could pose significant risks to road users and result in material damage.

3. Assessment of alternative road alignments:

Road authorities and specialized engineering companies should evaluate the possibility of modifying or locally rerouting sections of the road in both study areas, particularly where the road crosses very steep slopes and geological formations characterized by relatively high porosity and permeability. Such locations may be susceptible to different types of ground failure, particularly rapid and sudden failures.

4. Improvement of surface-water drainage:

Appropriate drainage channels and water-control measures should be established or improved in areas where rainfall runoff accumulates near unstable slopes. Controlling surface-water flow can reduce water infiltration into susceptible formations and consequently help limit erosion and slope instability.

5. Periodic monitoring of unstable sites:

The identified landslide and ground-failure sites should be periodically monitored, particularly during and after periods of heavy rainfall. Monitoring can help detect changes in slope conditions, cracks, displacement, or progressive deterioration and allow appropriate preventive measures to be implemented before major failures occur.

6. Detailed engineering and geological investigations:

Before implementing permanent protection measures or modifying road alignments, detailed geological, geotechnical, and hydrological investigations should be conducted. These investigations should consider lithology, discontinuities, slope geometry, groundwater and surface-water conditions, porosity, permeability, and the mechanical properties of the affected materials.

3. References



- Cruden, D. M., & Varnes, D. J. (1996). Landslide types and processes. In A. K. Turner & R. L. Schuster (Eds.), *Landslides: Investigation and Mitigation* (Transportation Research Board Special Report 247, pp. 36–75). National Academy Press.
- Highland, L. M., & Bobrowsky, P. (2008). *The Landslide Handbook: A Guide to Understanding Landslides*. U.S. Geological Survey Circular 1325.
- Hungr, O., Leroueil, S., & Picarelli, L. (2014). The Varnes classification of landslide types, an update. *Landslides*, 11, 167–194. <https://doi.org/10.1007/s10346-013-0436-y>
- Terzaghi, K. (1950). Mechanism of landslides. In S. Paige (Ed.), *Application of Geology to Engineering Practice* (pp. 83–123). Geological Society of America.
- Iverson, R. M. (2000). Landslide triggering by rain infiltration. *Water Resources Research*, 36(7), 1897–1910. <https://doi.org/10.1029/2000WR900090>
- Fredlund, D. G., & Rahardjo, H. (1993). *Soil Mechanics for Unsaturated Soils*. John Wiley & Sons.
- Dou, H.-Q., Han, T.-C., Gong, X.-N., & Zhang, J. (2015). Probabilistic slope stability analysis considering the variability of hydraulic conductivity under rainfall infiltration–redistribution conditions. *Engineering Geology*, 183, 1–13. <https://doi.org/10.1016/j.enggeo.2014.09.005>
- Tu, X. B., Kwong, A. K. L., Dai, F. C., Tham, L. G., & Min, H. (2009). Field monitoring of rainfall infiltration in a loess slope and analysis of failure mechanism of rainfall-induced landslides. *Engineering Geology*, 105(1–2), 134–150. <https://doi.org/10.1016/j.enggeo.2008.11.011>
- Cho, S. E. (2018). Prediction of shallow landslide by surficial stability analysis considering rainfall infiltration. *Engineering Geology*, 231, 126–138. <https://doi.org/10.1016/j.enggeo.2017.10.018>
- Marin, R. J., & Velásquez, M. F. (2020). Influence of hydraulic properties on physically modelling slope stability and the definition of rainfall thresholds for shallow landslides. *Geomorphology*, 351, 106976. <https://doi.org/10.1016/j.geomorph.2019.106976>
- Cho, S. E. (2009). Infiltration analysis to evaluate the surficial stability of two-layered slopes considering rainfall characteristics. *Engineering Geology*, 105, 32–43.



El-Hinnawy, M. E., & Cheshitev, G. (1975). Geological Map of Libya, Sheet Gharyan (NH 33-1), Scale 1:250,000.

Industrial Research Centre, Tripoli, Libya.

El-Zouki, A. V. (1980). Stratigraphy and lithofacies of the continental clastic (Upper Jurassic and Lower Cretaceous) of Jabal Nafusah, NW Libya. In M. J. Salem & M. T. Busrewil (Eds.), *The Geology of Libya* (Vol. II, pp. 394–418). Academic Press.

Hammuda, O. S., et al. (1991). Geological and stratigraphic studies of the Nafusa Mountain region, northwestern Libya. In *The Geology of Libya*. University of Tripoli/related geological publications.

Hodgkinson, R. J. (1980). Middle, Upper Jurassic and Lower Cretaceous sedimentary environments of the Djebel Nefusa region, northwestern Libya. In *The Geology of Libya*. Academic Press.