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Original article

Field and Laboratory Investigation of the Effect of Water Saturation Variation on the Progressive Instability of Soil Slopes Along the Al-Naqaza Mountain Road, Libya

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Abstract
This study aims to analyze the instability mechanism of cut earth slopes along the Al-Naqaza mountain road west of the city of Al-Khums, Libya, which consists of silty clay soil, by linking field observations with laboratory tests to assess the effect of moisture content on shear strength and slope stability. The study relied on direct field observations, in addition to sieve analysis and direct shear tests under different moisture conditions. The field results showed the presence of cracks and near-vertical joints, exposed plant roots, localized disintegration of surface layers, and the bending of some tree trunks, indicating the occurrence of soil creep. Sieve analysis also showed that the percentage of fine materials passing through a 0.075 mm sieve was approximately 60%, indicating a predominance of silt and clay particles and a poor grain size distribution of the soil. Direct shear tests showed that increasing the degree of saturation from partially saturated conditions to full saturation Sr=100% resulted in a reduction in the angle of internal friction from 32° to 10° and a decrease in cohesion from 8 t/m² to nearly 0 t/m², while the bulk density increased from 1.4 g/cm³ to 1.98 g/cm³, leading to a significant decline in shear strength and slope safety factor. The results indicate that the slope is undergoing progressive deterioration, manifested as surface collapses and shallow slides associated with increased saturation, soil weakness, and loss of natural support due to cutting operations.
Keywords. Silty Clay, Slope Stability, Soil Creep, Progressive Deterioration, Direct Shear Test.

Introduction

The stability of cut slopes along mountain roads is a critical geotechnical concern, particularly in mountainous regions where soil and rock masses are vulnerable to failure. Landslides are often intensified by natural conditions and human activities such as road excavation and vegetation removal [1]. Failures within these slopes may occur in the form of partial or complete landslides, posing risks to transportation networks and adjacent infrastructure [2]. The problem becomes more critical in slopes composed of silty clay soils due to their high sensitivity to hydrological and environmental variations. Changes in moisture conditions can progressively reduce the mechanical strength of the soil and accelerate slope deterioration over time [3].

From a geotechnical perspective, slope-cutting operations cause a redistribution of stresses within the soil mass [4]. The removal of part of the natural support at the slope toe increases active shear stresses and consequently reduces the factor of safety [4,5]. In silty clay soils, this condition becomes more critical due to the strong dependence of shear strength on moisture content. An increase in saturation raises pore water pressure and reduces effective stress, leading to a decrease in shear resistance [6]. In addition, cracks formed by drying and shrinkage, together with voids associated with root growth, act as preferential pathways for water infiltration into the slope body. This process accelerates the reduction of soil cohesion and promotes the formation of potential slip surfaces [6,7].

Although vegetation roots are commonly associated with improved near-surface stability through root reinforcement [8], field observations along the study area suggest a more complex response after slope cutting. Exposure of roots and partial detachment of the surrounding soil may contribute to the development of localized voids and extended cracks within the soil mass [9, 10]. Moreover, the horizontal extension of some roots along the slope surface may facilitate the formation of continuous weak zones that increase susceptibility to shallow collapses and localized slope failures, particularly under repeated wetting–drying cycles [11].

The cut slopes along the Al-Naqaza mountain road (Figure 1) exhibit several indicators of progressive instability. Field observations revealed partial loss of surface soil cover, exposure of tree roots, the presence of cracks and near-vertical joints within the soil mass, and localized surface detachment and disintegration. Horizontal and vertical root extensions protruding through the slope body further reflected ongoing deformation processes. Accordingly, this study aimed to investigate the instability indicators of cut earthen slopes of the cut earthen slopes along the Al-Naqaza mountain road by evaluating the influence of saturation variation on soil shear strength parameters and correlating laboratory findings with field observations.

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Figure 1. Cut slopes along the Al-Naqaza mountain road, Al-Khums.

The study area is located along the Al-Naqaza mountain road, west of the city of Al-Khums, Libya (Figure 2), at approximately 32.63°N and 14.30°E. The investigated section consists of a series of cut earthen and rocky slopes formed during road construction activities. The total length of the slopes parallel to the roadway is approximately 1.2 km, with noticeable variations in slope height and cut angle along different sections of the road.

Figure 2. Location of the study area

Methodology

Field Investigation

Field investigations were conducted along the cut slopes of the Al-Naqaza mountain road to evaluate slope conditions and identify visible indicators of instability. The site survey included the inspection of surface cracks, joints, erosion features, runoff traces, and localized zones of soil detachment. Attention was given to the influence of vegetation cover and root penetration on slope behavior and surface integrity. Geometrical characteristics of the slopes, including slope inclination and relative height variations, were also visually assessed during the investigation. Field conditions were documented through site photography and systematic visual observations, focusing on areas exhibiting progressive deterioration and potential shallow deterioration behavior.

Sieve Analysis of Soil Sample

A laboratory investigation was conducted on soil samples collected from the study area to classify the soil and evaluate its engineering behavior under different moisture conditions. Initially, sieve analysis was performed to determine the particle size distribution of the soil. Approximately 2000 g of soil was oven-dried at 120°C for 24 hours to remove natural moisture content in accordance with standard laboratory procedures [12]. The dried sample was subsequently passed through a series of standard sieves with aperture sizes ranging from 31.5 mm to 0.063 mm. The retained mass on each sieve was measured, and the corresponding retained and passing percentages were calculated. The obtained results are presented in (Table 1).

Direct Shear Test and Determination of Shear Strength Parameters

Following the granulometric analysis, direct shear tests (Figure 3) were conducted to determine the shear strength parameters of the soil, namely cohesion (c) and internal friction angle (φ). These parameters were later used to evaluate slope stability and examine the influence of moisture variation on soil behavior.

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Figure 3. Devices and Equipment Used in the Laboratory

The previously dried soil sample was used for the shear tests. Controlled quantities of water were added to prepare samples with different moisture conditions. After water addition, each sample was thoroughly mixed to achieve uniform moisture distribution before testing. The direct shear tests were then performed under controlled loading conditions to evaluate the variation in shear resistance with increasing moisture content. A direct shear testing apparatus with a shear box area of 36 cm² was used to evaluate the shear strength behavior of the soil (Figure 3). The tests were conducted at a constant shear displacement rate of 0.25 mm/min under three different normal loads of 4 kg, 8 kg, and 16 kg [13]. The obtained results were used to establish the relationship between normal stress and shear stress at failure and to determine the Mohr–Coulomb shear strength parameters of the soil. (Figure 4) illustrates the direct shear testing procedure.

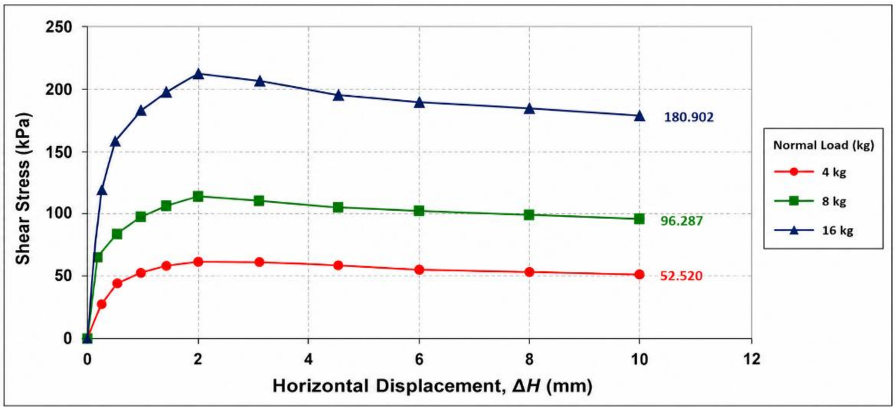

Figure 4. Direct shear behavior of the dry soil sample under applied normal loads of 4, 8, and 16 kg.

The experimental data were processed and analyzed to establish the relationship between normal stress and shear stress at failure in accordance with the Mohr–Coulomb failure criterion. Linear regression analysis was performed to define the failure envelope for each moisture condition. The cohesion (c) and internal friction angle (φ) were subsequently determined from the intercept and slope of the corresponding regression line, respectively (Figure 5).

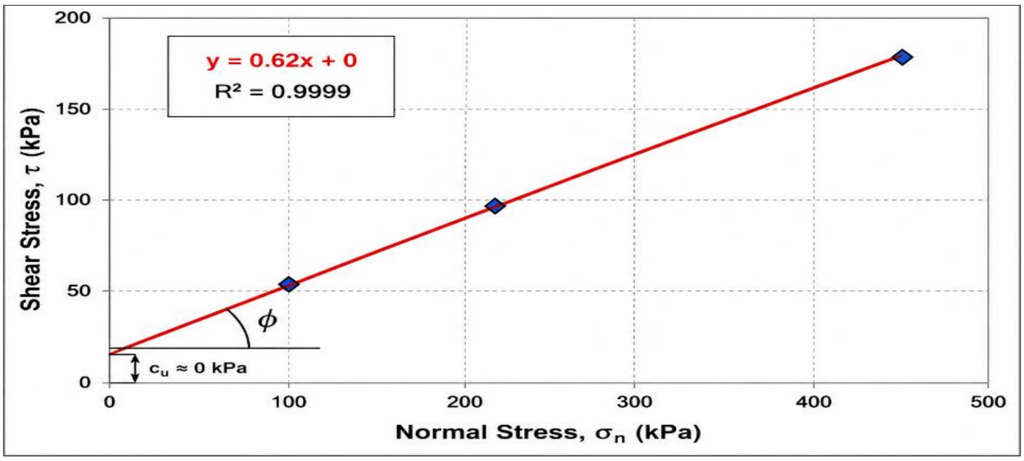

Figure 5. Relationship between normal and shear stress for the dry soil sample.

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Results and Discussion

Results of the Field Study

Field observations conducted along the cut slopes of the Al-Naqaza mountain road revealed progressive signs of instability within the soil mass. The investigated slopes had undergone extensive cutting operations, resulting in the removal of a significant portion of the natural toe support and the exposure of the upper soil layers (Figure 6). As a result, tree roots became visibly exposed along several sections of the slope face.

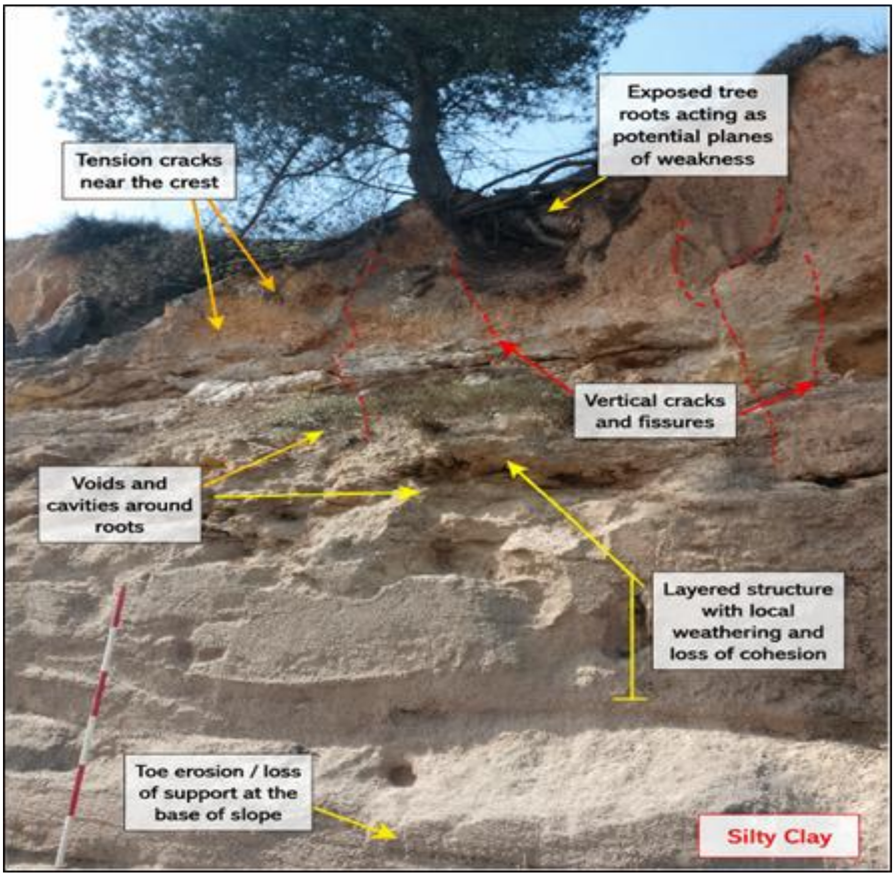

Figure 6. Field indicators of slope instability in soil.

Figure 6 shows exposed root systems extending through the soil mass, together with localized voids and gaps formed by the partial detachment of the surrounding soil. In addition, cracks and near-vertical joints were observed in the upper parts of the slope, indicating the progressive development of internal weak zones associated with repeated wetting–drying cycles.

These field conditions suggest that root exposure and soil detachment may contribute to localized weakening within the slope body. The voids surrounding exposed roots can act as preferential pathways for water infiltration, facilitating moisture penetration into deeper soil layers. This process may increase pore water pressure, reduce effective stress, and consequently decrease the shear strength of the soil.

(Figure 7) illustrates progressive surface deterioration along the slope, including exposed root extensions, localized soil disintegration, and shallow surface collapses. Extensive cracking and granular breakdown of the soil can also be observed, indicating progressive weakening of the slope material under the influence of environmental weathering and moisture fluctuations. In several sections, horizontally extending roots appear to coincide with the development of continuous weak zones near the slope surface. These zones may facilitate the formation of shallow slip surfaces under conditions of increased water infiltration and repeated wetting–drying cycles.

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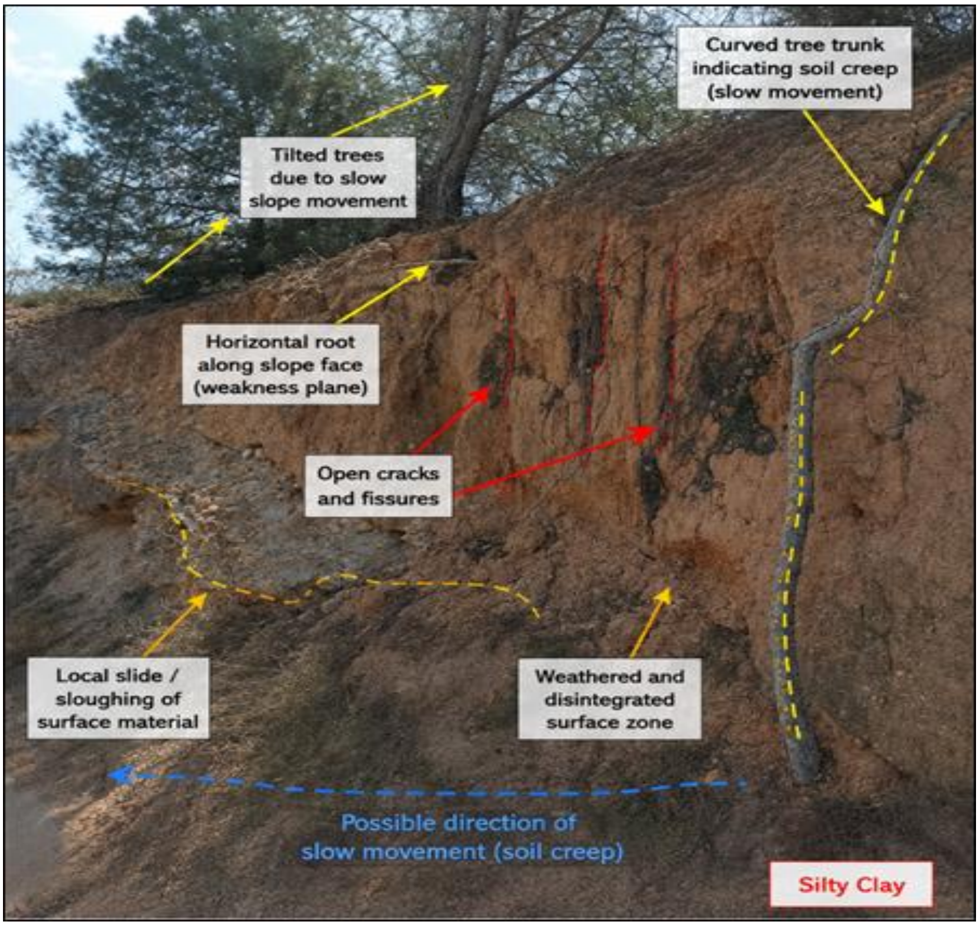

Figure 7. Field evidence of soil creep and progressive slope movement

Field observations (Figure 7) revealed a noticeable curvature in the trunk of a tree located near the crest of the slope. This deformation is commonly recognized as a geomorphological indicator of soil creep, where slow and continuous downslope soil movement gradually displaces the tree base while the trunk continues to grow vertically. As a result, trunk curvature develops over time. The observed deformation suggests the presence of long-term shallow slope movement, particularly within silty clay soils that are highly sensitive to moisture variation and repeated wetting–drying cycles. These conditions may indicate an early stage of progressive instability preceding localized surface failures.

The field observations are consistent with geotechnical principles governing the behavior of silty clay soils under hydrological influence. Increased moisture infiltration may reduce both effective cohesion (c) and internal friction angle (ϕ), leading to a decrease in shear strength and overall slope stability. In addition, the visible erosion, soil disintegration, cracking, and root exposure observed along the slope face indicate that instability is developing progressively rather than as a sudden failure event. This behavior appears to result from the combined effects of stress redistribution following slope cutting, moisture infiltration, and progressive weakening of the soil structure caused by cracking and localized detachment around exposed roots.

Sieve analysis results

The sieve analysis results and grain size distribution data (Table 1) indicate that the tested soil is predominantly fine-grained with silty clay characteristics. Approximately 60% of the material passed through the 0.075 mm sieve, reflecting the dominance of silt and clay fractions within the soil matrix.

Table 1. Grain size distribution and sieve analysis results of the tested soil sample

Size (mm)	Retained (g)	% Retained	Cum. % Retained	% Passing
31.50	0	0.0	0.0	100
16.00	0	0.0	0.0	100
10.00	0	0.0	0.0	100
8.00	0	0.0	0.0	100
4.00	0	0.0	0.0	100
2.00	0	0.0	0.0	100
1.00	0	0.0	0.0	100

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0.600	0	0.0	0.0	100
0.425	0	0.0	0.0	100
0.250	80	4.0	4.0	96
0.150	160	8.0	12.0	88
0.125	200	10.0	22.0	78
0.075	360	18.0	40.0	60 ✓
0.063	300	15.0	55.0	45
Pan	900	45.0	100.0	0

In contrast, the proportion of coarse particles was relatively low, with only a minor sand fraction and an almost complete absence of gravel-sized particles. This grain size distribution suggests that the engineering behavior of the soil is mainly controlled by fine-grained material properties, particularly its sensitivity to moisture variation and changes in saturation. The high percentage of fine particles is consistent with the field observations of cracking, surface disintegration, and progressive weakening observed along the investigated slopes.
This type of soil is highly susceptible to instability under repeated wetting–drying cycles due to the high water-retention capacity of silt and clay particles and their sensitivity to moisture variation. Increased moisture infiltration may promote higher pore water pressures and reduce effective stress within the soil mass [14], resulting in a decrease in shear strength parameters, including cohesion and internal friction angle. This behavior is consistent with the field observations of cracking, surface disintegration, and localized deterioration along the slopes of the Al-Naqaza mountain road.
In addition, the grain size distribution curve presented in Figure 8 indicates a predominance of fine particles within the soil matrix, with limited representation of coarse fractions. The dominance of fine-grained material contributes to reduced drainage capability and increased moisture retention, making the soil more vulnerable to erosion, softening, and shallow surface instability under saturated conditions.

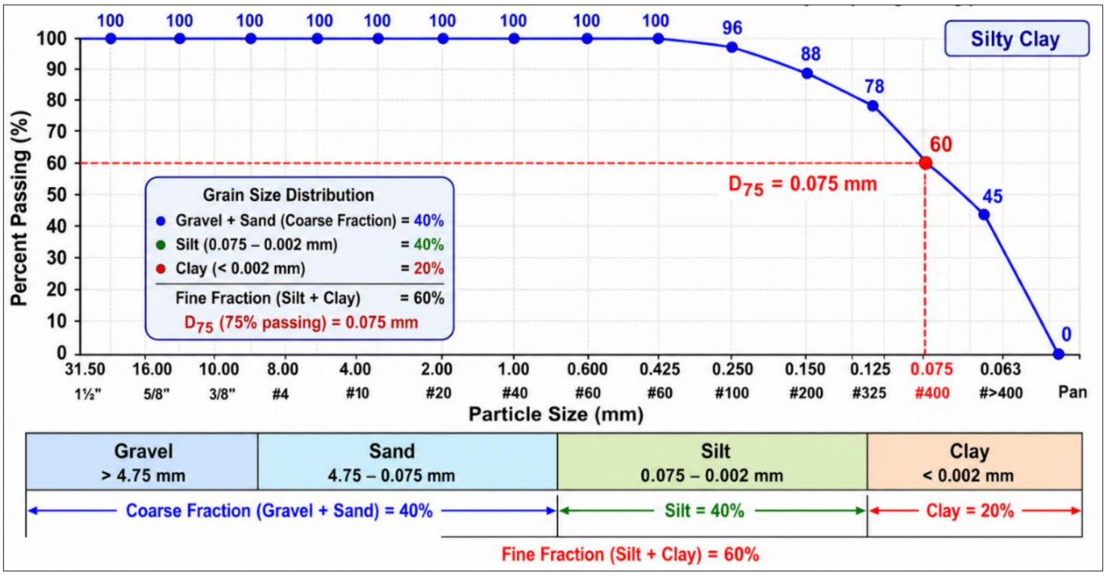

Figure 8. Grain size distribution curve of the silty clay soil sample

The sieve analysis results are consistent with the field observations, which revealed localized surface disintegration, exposed roots, and near-vertical cracking within the slope body. Silty clay soils are particularly susceptible to shrinkage and crack development during drying periods, followed by a substantial reduction in strength upon re-wetting, as reported in previous studies [14]. In addition, the presence of exposed roots within the slope may locally influence the mechanical behavior of the soil after cutting operations. Partial root exposure, root decomposition, and detachment of the surrounding soil can contribute to the formation of localized voids and preferential pathways for water infiltration into the slope mass.
Based on both field observations and laboratory findings, the instability mechanism of the investigated slope appears to result from the combined interaction of several factors, including the predominance of fine-grained material, moisture fluctuations associated with wetting–drying cycles, progressive cracking and soil weakening, and stress redistribution caused by slope cutting operations.

Results of Direct Shear Tests
Table 2 presents the effect of saturation on the geotechnical properties of the tested silty clay soil. The results indicate a clear relationship between increasing saturation and the progressive reduction in shear strength.

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Increasing the amount of water added to the sample from 0 ml to 70 ml resulted in a gradual increase in saturation from 0.5% to 100%, which was directly reflected in the values of cohesion (c) and internal friction angle (ϕ). Both parameters showed a noticeable decrease with increasing saturation, indicating deterioration in the mechanical behavior of the soil and an increased susceptibility to instability under wet conditions.

Table .2 Effect of saturation on the geotechnical properties of silty clay soil.

Parameter	0 ml	10 ml	30 ml	50 ml	70 ml
Water Saturation (%)	0.5	15.6	46.8	76	100
Friction Angle (°)	32	29	24	20	10
Cohesion (t/m²)	0	8	5	2	0
Unit Weight (g/cm³)	1.40	1.59	1.70	1.82	1.98
Slope Height (m)	3	3	3	3	3

The results indicate that the internal friction angle (ϕ) decreased progressively from 32° under relatively dry conditions to 10° at the highest water saturation. This significant reduction reflects the loss of the soil's ability to resist sliding as moisture conditions increase. The reduction in friction angle can be attributed to the increase in pore water pressure and the corresponding decrease in effective stress between soil particles, which reduces the internal friction forces that constitute a major component of shear resistance in silty clay soils.

Table 2 shows that the cohesion (c) of the tested silty clay soil exhibited a nonlinear behavior with increasing water saturation. Under near-dry conditions (0.5%), the measured cohesion was approximately 0 ton/m². As the water saturation increased to about 15.6%, the cohesion value increased significantly to nearly 8 ton/m². This temporary increase can be attributed to the effect of matric suction and capillary forces developed within the partially unsaturated soil, which generated an apparent cohesion between soil particles, consistent with the findings reported in Reference [15]. With further increases in saturation to 46.8% and 76%, the cohesion gradually decreased to approximately 5 ton/m² and 2 ton/m², respectively (Figure 9). Under conditions approaching full saturation (100%), the cohesion value approached zero due to the dissipation of matric suction and the weakening of interparticle bonds caused by increased pore-water saturation. This behavior reflects the typical geomechanical response of unsaturated silty clay soils, where limited moisture content may temporarily enhance apparent cohesion, whereas high saturation levels result in a substantial reduction in shear strength and overall slope stability, in agreement with the results reported in Reference [16].

It can also be observed that the bulk density of the soil increased progressively with increasing saturation (Figure 9), rising from approximately 1.4 g/cm³ to 1.98 g/cm³. This increase reflects the additional water retained within the soil mass and results in higher self-weight loading acting on the slope. Consequently, the driving forces acting downslope become greater, particularly under conditions where the slope geometry remains unchanged. The combined effect of increasing soil unit weight and decreasing shear strength parameters contributes to a progressive reduction in slope stability and increases the likelihood of shallow slope failure under high moisture conditions.

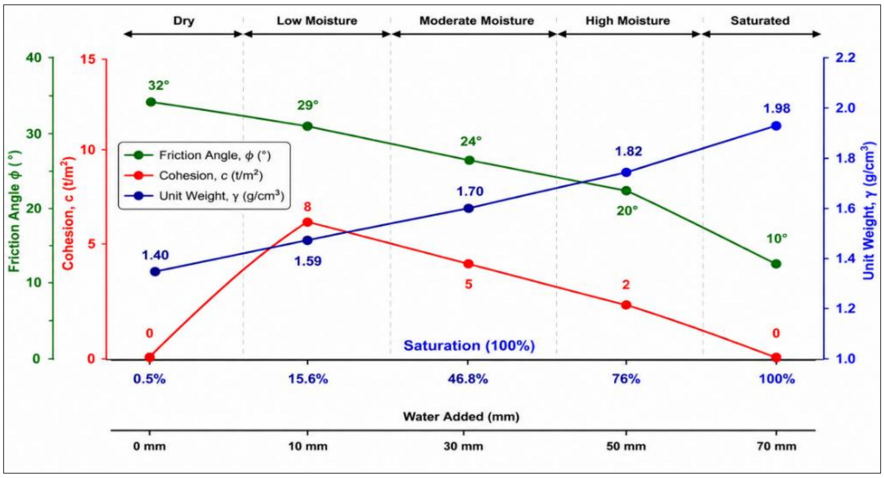

Figure 9. Relationship Between Water Saturation and Shear Strength Parameters

These findings are consistent with the field observations obtained from the slopes in the Al-Naqaza area, where visible cracking, localized soil disintegration, exposed roots, and indications of slow soil creep were identified. The presence of cracks and exposed root zones facilitates water infiltration into the soil mass, progressively increasing the saturation and contributing to the deterioration of the soil's mechanical properties, as demonstrated in (Table 2). In particular, the significant reduction in the internal friction angle

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under high moisture conditions provides a reasonable explanation for the shallow surface collapses and progressive disintegration observed along the slope face.

Conclusion

This study investigated the instability of cut slopes along the Al-Naqaza mountain road near Al-Khums, Libya, through field observations and laboratory testing. The investigated slopes consist predominantly of fine-grained silty clay soil that is highly sensitive to moisture variation. Field observations revealed progressive instability indicators, including cracking, exposed roots, surface disintegration, and signs of soil creep. Laboratory results showed that increasing saturation significantly reduces the soil shear strength parameters, particularly the internal friction angle and cohesion, while increasing soil unit weight. These combined effects contribute to progressive slope weakening and increase the susceptibility to shallow failures and localized landslides. Overall, the study confirms that moisture infiltration and slope cutting are key factors controlling the progressive deterioration of silty clay cut slopes in the study area.

Future Investigation

Future investigations are recommended to include numerical slope stability analyses using advanced geotechnical software packages such as GeoStudio, Slide2, and PLAXIS 2D to evaluate the influence of moisture variations on slope behavior under dry, saturated, and transient infiltration conditions. These analyses may consider the development of pore-water pressure, identification of critical slip surfaces, reduction in the Factor of Safety (FOS) with increasing moisture content, and sensitivity analyses of shear strength parameters. Furthermore, incorporating seepage analysis, unsaturated soil mechanics, and long-term slope monitoring would provide a more comprehensive understanding of progressive slope deterioration under repeated wetting–drying cycles and varying environmental conditions.

Conflict of interest. Nil

References

1. Mansur A, Alakhdar A. Simulation of a Marl Rock Slope Failure Parallel to the Nalut Mountain Road, Libya. AlQalam J Med Appl Sci. 2025 Aug 16;8(3):1721-6.
2. Alcántara-Ayala I. Landslides in a changing world. Landslides. 2025 Sep;22(9):2851-65.
3. Lari M., Samani AN, Tariq A, Jondani SA, Rebouh NY. Quantifying sediment yield and discharge fluctuations using the GeoWEPP in response to soil and water conservation practices. Int J Sediment Res. 2026 Apr;41(2):344-57.
4. Jiang LF, Gao SR, Yin XT, Qin H. Characteristics of excavation unloading deformation and reinforcement force estimation method considering stress compensation for differential weathering slopes in valley areas. Bull Eng Geol Environ. 2026 May;85(5):288.
5. Bera B. A geotechnical investigation on a recent gigantic rock avalanche at the Patalganga-Langsi site on the Badrinath highway of Chamoli, Uttarakhand (Garhwal Himalaya), India. Discov Geosci. 2025 Sep 13;3(1):120.
6. Alakhdar A. Effect of water saturation changes on the creep and stability of the soil slope parallel to the Al-Qawasim Mountain Road. Sharwes J. 2025 Jun 25;6(1):338-1.
7. Afolayan O. Multiscale physical model on internal erosion in unsaturated slope [dissertation/thesis]. 2025.
8. Cao Y, Su X, Zhou Z, Liu J, Chen M, Wang N, Zhu B, Wang P, Liu F. Effects of root traits on shear performance of root-soil complex and soil reinforcement in the Loess Plateau. Soil Tillage Res. 2025 Oct 1;252:106625.
9. Duan X, Yang Z, Wang B, Chen C, Qu J, Chang Y, Shi L, Yan H, Dong Q, Ye W. Time-varying tensile resistance mechanisms in slope-protecting alfalfa roots. Plant Soil. 2026 Mar 26:1-21.
10. Xu R, He Y, Cheng H, Deng J, Wei H, Wang G, Li X, Yang W. Mechanical mechanism of soil consolidation by plant roots in loess area of northern Shaanxi. Sci Rep. 2025 Mar 7;15(1):8014.
11. Meng J, Yan E, Wu Y, Yang B, Miao F, Wang Y, Zhan W. Long-term stability of landslide considering the strength degradation of slip zone soil under coupled drying-wetting cycles with loading. Bull Eng Geol Environ. 2025 Nov;84(11):527.
12. Alakhdar A. Analyzing the Stability and Safety of Artificial Slopes along the Alwadi Road in Sabratha City, Libya. AlQalam J Med Appl Sci. 2025 Jul 19;8(2):1444-50.
13. Alakhdar A. Effect of Gully Erosion on the Slope Parallel to the Al-Rujban Mountain Road NW Libya. Gharyan Univ J Eng Sci. 2025 Sep 15;1(1):28-37.
14. Dong M, Deng Y, Fu Y. Cracking behavior and deterioration of strength characteristics of silty clay under drying-wetting cycles. Bull Eng Geol Environ. 2025 Apr;84(4):205.
15. Abd IA, Fattah MY, Mekkiyah H. Relationship between the matric suction and the shear strength in unsaturated soil. Case Stud Constr Mater. 2020 Dec 1;13:e00441.
16. Lan T, Zhang R, Yang B, Meng X. Influence of swelling on shear strength of expansive soil and slope stability. Front Earth Sci. 2022 Apr 6;10:849046.

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