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Geotechnical Characterization and Shear Strength Behavior of Interbedded Clay Layers in the Ain Tabi Member, Al-Asaba, Libya

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ABSTRACT

Purpose: This study aimed to evaluate the geotechnical properties and shear strength behavior of the interbedded clay layers of the Ain Tabi Member along the Al-Bayyib Mountain Road, Al-Asaba, Libya, and to assess the influence of increasing moisture content on their engineering performance and implications for slope stability.

Materials and Methods: Representative samples were collected from the interbedded clay layers and tested in the laboratory. Grain size distribution was determined using sieve analysis, while direct shear tests were performed under five different moisture conditions to investigate variations in shear strength parameters.

Results: The tested material was classified as Clayey Sand (SC), comprising 74% sand, 24% fines, and 2% gravel. Increasing water content caused a marked reduction in shear strength. Cohesion decreased from 13.8 to 7.8 kPa, while the internal friction angle declined from 36.8–38.4° to 15.3%. Conversely, the wet unit weight increased from 1.85 to 2.08 g/cm³. These changes resulted from reduced matric suction, loss of particle interlocking, and the lubricating effect of water, which collectively weakened the soil structure.

Conclusion: Moisture content is a critical factor controlling the mechanical behavior of the interbedded clay layers. The significant reductions in cohesion and friction angle with increasing water content can substantially decrease slope stability. These findings provide valuable geotechnical data for slope stability assessment and support the implementation of appropriate drainage and stabilization measures in moisture-sensitive slopes. *(J Multidiscip Eng 2026;1:68-75)*

Keywords: Interbedded clay layers, Shear strength, Slope stability.

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1. INTRODUCTION

The geotechnical properties of soils and rocks are among the most important factors controlling the stability of engineering structures, particularly mountain roads and rock slopes, where soil behavior under applied loads depends on its grain size distribution, density, water content, and shear strength characteristics.[1] Interbedded clay layers are considered one of the geological units most sensitive to environmental changes, as variations in moisture content can significantly alter their mechanical properties,[2, 3] leading to reduced shear strength and an increased susceptibility to landslides and slope instability.[4]

Shear strength is one of the most critical engineering properties considered in the design of foundations, slopes, and transportation

infrastructure, as it represents the soil's ability to resist sliding forces. [5]

According to the Mohr Coulomb failure criterion, shear strength is primarily governed by cohesion (c) and the internal friction angle (φ), both of which are influenced by several factors, including soil type, particle size distribution, density, and degree of water saturation. [6] In general, increasing water content reduces cohesion and particle friction through the dissipation of matric suction, thereby adversely affecting soil stability.

Sieve analysis is a fundamental laboratory test for soil characterization, as it determines particle size distribution and the proportions of gravel, sand, and fine particles, which directly influence permeability, compressibility, compaction characteristics, and soil behavior under loading. [7] Clayey sandy soils containing a considerable percentage of fines exhibit significant changes in their engineering properties with variations in moisture content, making it essential to investigate the influence of water on shear strength under different field conditions. [8]

The study area is located along the Al-Bayyib–Al-Asaba Mountain Road, where the Ain Tabi Member is exposed and contains interbedded clay layers of considerable geological and engineering significance (Fig.1).

These layers are continuously subjected to weathering processes and seasonal moisture fluctuations, making them particularly vulnerable to strength degradation, deformation, and slope failure that may threaten the stability of the road and adjacent engineering structures. Despite the engineering importance of this area, studies addressing the geotechnical characteristics of these interbedded clay layers and the influence of moisture content on their mechanical behavior remain limited.

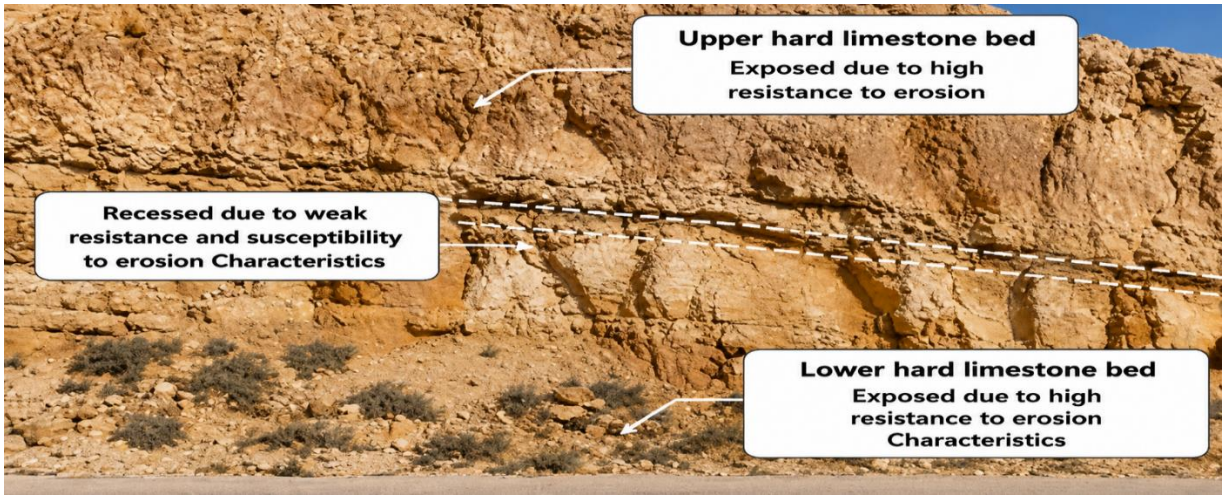


Fig 1. Road-cut exposure of the Ain Tabi Member showing interbedded clay layers.

Therefore, this study aims to evaluate the geotechnical properties and shear strength behavior of the interbedded clay layers within the Ain Tabi Member along the Al-Bayyib–Al-Asaba Mountain Road. The investigation was carried out through sieve analysis to determine the grain size distribution and direct shear tests performed under different water contents to assess the effect of moisture on cohesion and the internal friction angle. (Fig.2) shows the geographical location of the study area, which is situated north of Al-Asaba City on the northern escarpment of the Nafusa Mountains, along the Al-Bayyib–Al-Asaba Mountain Road. The road extends between Jandouba Village at the mountain foothills and Al-Rabita Village at the base of the escarpment. The study area is located between latitudes 32°08′07″N and 32°08′09″N, and longitudes 12°51′42″E and 12°51′56″E.

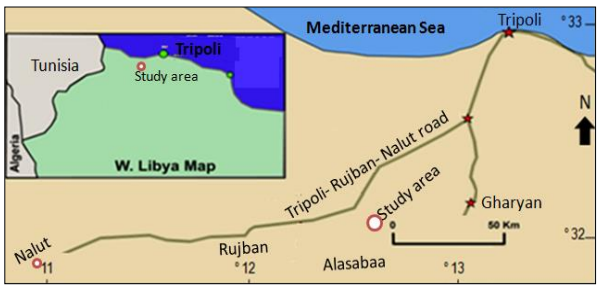


Fig 2. Geographic location of the study area.

The sedimentary succession exposed along the slopes adjacent to the Al-Bayyib Mountain Road comprises several Lithostratigraphic units. The most prominent outcrops include the Bir Al-Ghanam Formation (Gypsum) and the Abu Ghailan Formation (Limestone), which are overlain by the Kiklah Formation and the Sidi Al-Said Formation, represented by the Ain Tabi Member and the Yefren Marl Member. The Bir Al-Ghanam Formation forms the lower part of the study area slopes. The geological succession extends from the Lower Triassic, beginning with the Qarash Formation, to the early Cenozoic, represented by the Zmam Formation.[9]

2. MATERIALS AND METHODS

2.1 Sample Collection

A field survey was conducted to identify road-cut outcrops of the interbedded clay layers within the Ain Tabi Member (Fig.3) and to select representative sampling sites that reflect the prevailing geological conditions along the Al-Bayyib Mountain Road.

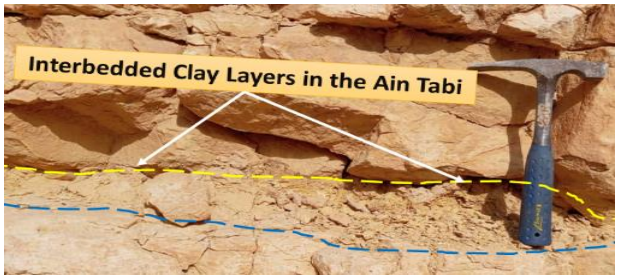


Fig 3. Interbedded clay layers within the Ain Tabi.

Representative samples were collected from the investigated clay layers, and transported to the laboratory for subsequent geotechnical testing.

2.2 Laboratory Study

The laboratory study aimed to evaluate the geotechnical properties and shear strength of the interfacial clay layers of a natural eye organ by determining the soil particle size distribution, calculating the water content, wet bulk density, cohesion coefficient (C), and angle of internal friction (φ), as well as studying the effect of increasing water content on these properties. A set of laboratory instruments and equipment was used to conduct the tests, as shown in Fig. 4.



Fig 4. Some of the laboratory equipment and instruments used in this study.

2.2.1 Sieve Analysis

Sieve analysis was conducted to determine the particle size distribution of the sample in accordance with the relevant standard testing procedures.[9] A series of standard sieves was used to determine the proportions of gravel, sand, and fine particles (Table 1), after which the soil was classified based on its particle size distribution.

Table 1: Standard Sieves Used in the Sieve Analysis Test.

No.	Sieve Opening .mm	Purpose
1	31.50	Separation of coarse gravel
2	16.00	Separation of gravel
3	10.00	Separation of gravel
4	8.00	Separation of gravel
5	4.75	Boundary between gravel and sand
6	2.00	Coarse sand
7	1.00	Medium sand
8	0.600	Medium to fine sand
9	0.425	Fine sand
10	0.250	Fine sand
11	0.150	Very fine sand
12	0.075	Boundary between sand and fines
13	Pan	Material passing the 0.075 mm

Source [10]

Following sample collection from the study area, the specimens were transported to the laboratory in sealed plastic bags to preserve their natural moisture content. A portion of each sample was used to determine the natural water content by oven-drying at 120°C for 24 hours.[11] Subsequently, the samples were prepared for geotechnical testing. Sieve analysis was then performed using the standard sieves listed in Table 1 to determine the particle size distribution and calculate the

percentages of gravel, sand, and fines, allowing the sample to be classified according to its engineering characteristics.[12]

2.2.2 Direct Shear Test

The direct shear test was conducted in accordance with ASTM D3080 to determine the shear strength parameters of the tested soil.[13]

The test was performed using a shear box with a cross-sectional area of 36 cm² and a constant displacement rate of 0.25 mm/min.The specimens were tested under three levels of normal stress (4, 8, and 16 kg).[14] As summarized in Table 2.

Table 2: Direct Shear Test Results for Clayey Sand at 5 mL Water Addition.

Parameter	4 kg	8 kg	16 kg
Sample Height (cm)	2.70	2.60	2.90
Sample Dimensions	6 × 6 cm²		
Loading rate	0.25 mm/min		
Sample Volume (cm³)	97.2	93.6	104.4
Wet Unit Weight, (g/cm³)	///		

To investigate the effect of water content on the behavior of the tested soil, incremental amounts of water (5, 10, 20, 30, 40, and 50 mL) were added to the dry samples, resulting in water contents ranging from 9.15% to 45%. After each water addition, the sample was thoroughly mixed to ensure a uniform distribution of moisture throughout the specimen. The direct shear test was then performed under the same normal loads used for the reference condition to evaluate the influence of increasing water content on the shear strength parameters.

Horizontal displacement and the corresponding shear stress values were recorded for each applied normal load. These measurements were subsequently used to calculate the shear strength and to determine the cohesion (c) and internal friction angle (φ) of the tested soil. Table 3 presents a representative set of direct shear test data obtained after the addition of 5 mL of water.

Table 3: Direct Shear Test Data for the Soil Sample after Adding 5 mL of Water**.**

Load Dial Reading (0.02 mm)	Horizontal Displacement ΔH (mm)	Shear Stress τ (kPa) 4 kg	Shear Stress τ (kPa) 8 kg	Shear Stress τ (kPa) 16 kg
0	0.0	0.000	0.000	0.000
13	0.1	7.586	27.427	59.523
22	0.2	12.838	38.515	76.446
34	0.4	19.841	49.602	100.372
49	0.8	28.594	64.191	136.552
66	1.5	38.515	85.783	180.902
76	2.0	44.350	97.454	203.661
92	3.0	53.687	117.878	229.337
113	4.5	65.942	135.968	255.597
129	6.0	75.279	151.724	278.940
147	8.0	85.783	172.732	306.950
163	**10.0**	**95.120**	**185.571**	**339.338**

In the final stage of the study, the results of all laboratory tests were compiled into tables and graphical representations. The relationships between increasing water content and cohesion (c), internal friction angle (φ), and wet unit weight (γ_{wet}) were then analyzed to evaluate the influence of moisture on the geotechnical properties of the interbedded clay layers within the Ain Tabi Member and to assess the implications of these changes for the stability of the overlying rock slopes.

3. RESULTS AND DISCUSSION

3.1 Grain Size Analysis and sample Classification

The grain size distribution of the interbedded clay layer was determined by sieve analysis in accordance with the standard testing procedures described in the methodology. The results are

presented in Table 4.

Table 4 indicates that the tested material consists predominantly of sand-sized particles (74%), accompanied by 24% fines (particles passing the 0.075 mm sieve) and only 2% gravel-sized particles. This particle size composition indicates that the soil is dominated by coarse-grained material, with a considerable proportion of fine particles that significantly influence its engineering behavior, particularly under varying moisture conditions.

Table 4: Grain Size Distribution of the Tested Soil Sample.

Sieve Size (mm)	Retained (g)	Retained %	Cumulative % Retained	Passing %
31.50	0	0	0	100
16.00	0	0	0	100
10.00	0	0	0	100
8.00	0	0	0	100
4.75	20	2	2	98
2.00	40	4	6	94
1.00	70	7	13	87
0.600	90	9	22	78
0.425	100	10	32	68
0.250	110	11	43	57
0.150	100	10	53	47
0.075	230	23	76	24
Pan	240	24	100	0
Gravel 2%		**Sand 74%**		**Fines 24%**

Based on the Unified Soil Classification System (USCS), the tested material is classified as Clayey Sand (SC), since sand represents the dominant fraction while the percentage of fines exceeds the threshold required for coarse-grained soils containing significant clay-sized particles. This classification is consistent with field observations, where thin clay-rich interbeds are enclosed between resistant limestone layers of the Ain Tabi Member.

The selection of this material for investigation was motivated by its engineering significance within the study area. Although the surrounding limestone beds exhibit high strength and resistance to weathering, the interbedded clay layers represent mechanically weaker horizons that are highly sensitive to changes in moisture content. Consequently, these layers are considered the most probable zones for shear deformation and potential slope instability along the Al-Bayyib Mountain Road.

3.2 Effect of Water Content on Shear Strength

The shear strength parameters obtained from the direct shear tests under different water contents are summarized in Table 5. The results clearly demonstrate that increasing the water content significantly altered the mechanical behavior of the tested interbedded clay layer. Three distinct trends were observed: a continuous decrease in cohesion, a progressive reduction in the internal friction angle, and a steady increase in the wet unit weight.

Table 5: Shear Strength Properties of Clayey Sand under Different Water Contents.

Water Quantity (mL)	Water Content (%)	Cohesion (kPa)	Friction Angle (°)	Unit Weight (g/cm³)
5	9.15	13.8	36.8	1.85
10	12.0	12.0	38.4	1.88
20	18.0	10.7	37.5	1.92
30	28.0	9.5	33.0	1.98
40	38.0	8.0	25.0	2.03
50	45.0	7.8	15.3	2.08

As shown in (Table 5), the cohesion (c) decreased continuously with increasing water content. At a water content of 9.15%, the cohesion was 13.8 kPa, which decreased to 12.0 kPa at 12%, 10.7 kPa at 18%, and 9.5 kPa at 28%. A more pronounced reduction was observed at higher moisture contents, where the cohesion declined to 8.0 kPa at 38% and finally reached 7.8 kPa at 45%. Overall, cohesion decreased by approximately 43.5%, indicating a progressive loss of bonding strength between soil particles. This reduction is mainly attributed to the gradual dissipation of matric suction, which provides apparent cohesion in partially saturated soils. As the degree of saturation increased, capillary forces diminished, resulting in weaker interparticle bonding and lower shear resistance.

The internal friction angle (φ) exhibited a different pattern. At relatively low water contents, the friction angle remained nearly constant, increasing slightly from 36.8° at 9.15% water content to 38.4° at 12%, before decreasing marginally to 37.5° at 18%. This behavior indicates that the soil skeleton and particle interlocking were largely preserved during the early stages of wetting. However, once the water content reached 28%, the friction angle decreased markedly to 33.0°, followed by a sharp decline to 25.0° at 38%, and finally to 15.3° at 45% water content. This substantial reduction reflects the progressive destruction of particle interlocking, the reduction in effective stress, and the lubricating effect of water films surrounding soil particles, which facilitated particle sliding during shearing.

Although both shear, strength parameters decreased with increasing water content, they responded differently to wetting. The reduction in cohesion began immediately as water content increased, whereas the internal friction angle remained relatively stable until the water content exceeded approximately 28%. Beyond this threshold, the rapid decrease in friction angle became the dominant factor controlling the reduction in shear strength, indicating that the soil structure had undergone significant degradation as saturation increased.

The wet unit weight increased steadily from 1.85 g/cm³ at 9.15% water content to 1.88, 1.92, 1.98, 2.03, and finally 2.08 g/cm³ at 45% water content.

This increase resulted from the gradual replacement of air within the pore spaces by water, producing a higher bulk density. Nevertheless, the increase in unit weight did not improve the mechanical behavior of the soil because it was accompanied by substantial reductions in both cohesion and internal friction angle.

Overall, the results reveal a strong negative correlation between water content and both cohesion and internal friction angle, whereas a positive correlation exists between water content and wet unit weight. The simultaneous reduction of cohesion from 13.8 to 7.8 kPa and friction angle from 36.8°–38.4° to 15.3° significantly reduced the shear strength of the interbedded clay layers. These findings explain the field observations in the Ain Tabi Member, where increased moisture weakens the clay-rich interbeds beneath the resistant limestone layers, promoting preferential weathering, erosion, and the formation of potential slip surfaces along the Al-Bayyib Mountain Road. Furthermore, these results are consistent with previous geotechnical studies, which have reported that increasing moisture reduces shear strength through the combined effects of matric suction loss, reduced particle interlocking, and the lubricating action of pore water.

3.3 Engineering Implications

3.3.1 Implications for the Stability of the Al-Bayyib Mountain Road

The results of the direct shear tests demonstrate that increasing water content substantially reduces the shear strength of the interbedded clay layers, primarily through decreases in cohesion and internal friction angle. Since these weak layers are interbedded between competent limestone beds, their strength governs the overall stability of the rock slopes along the Al-Bayyib Mountain Road. Under dry conditions, the clay layers provide sufficient shear resistance to support the overlying limestone; however, as moisture increases, their ability to resist shear stresses decreases significantly, increasing the likelihood of slope instability and localized rock failures.

3.3.2 Interbedded Clay Layers as Potential Slip Surfaces

The interbedded clay layers represent the weakest horizons within the Ain Tabi Member because of their relatively high fine-particle content and pronounced sensitivity to moisture. The laboratory results indicate that cohesion decreased from 13.8 kPa to 7.8 kPa, while the internal friction angle declined from approximately 37° to 15.3° as water content increased. Such reductions substantially decrease the shear resistance of the clay layers, making them the most probable locations for the initiation and propagation of failure surfaces. Consequently, these layers act as preferential slip surfaces beneath the stronger limestone beds during periods of increased moisture.

4. CONCLUSION

This study evaluated the geotechnical behavior of the interbedded clay layers within the Ain Tabi Member along the Al-Bayyib Mountain Road, with particular emphasis on the influence of moisture on shear strength. The findings confirm that variations in water content play a fundamental role in controlling the mechanical behavior of these clay-rich interbeds, which represent the weakest horizons within the rock sequence and significantly influence slope stability. From an engineering perspective, the study highlights the importance of considering moisture-induced changes in the design, assessment, and maintenance of road cuts developed in the Ain Tabi Member. Appropriate drainage measures and water infiltration control are therefore essential to reduce the likelihood of shear failure and improve the long-term stability of the slopes.

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AUTHOR CONTRIBUTIONS

Abd albasit Shalfouh: Conceptualization, methodology, writing – original draft, investigation, data curation, manuscript preparation, and final approval of the manuscript. **Osama Elghoul:** Investigation, data curation, validation, manuscript preparation, critical review, writing – review & editing, and final approval of the manuscript. **Saleh Emhanna:** Conceptualization, methodology, writing – original draft, investigation, data curation, manuscript preparation, and final approval of the manuscript.

CONFLICT OF INTEREST

The authors declare no conflicts of interest concerning the research, authorship, and publication of this article.

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