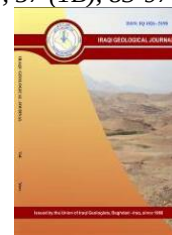




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The Role of Geological and Geotechnical Factors in Shale Slope Instability: Case of Landslides on Road Embankments, Tizi Ouadrene Sector - Rif Extern, Morocco

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Abstract

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Constructing roads in geologically unstable regions such as northern Morocco poses a major challenge. The Tizi Ouadrene sector, located in the Rif External Nappe of the Rif Belt, exemplifies a significant complexity in this issue, with a risk of landslides threatening the road embankments in this area. This study aims to characterize the frequent Cretaceous shales in the study area and analyze the landslides that have occurred on the road embankments cut into these shales. It examines the role of lithology, geometry, tectonics, human activity, and water in these landslides. The geological structure of slopes and their geometric configuration are crucial factors in determining the occurrence, distribution, and other characteristics of these landslides. Defects are controlled by the relative position of sedimentary and tectonic discontinuities, as well as the relative abundance of indurated shales compared to crushed ones. Crushed shales are susceptible to rotational slides, while the indurated ones are prone to planar and wedge sliding. The latter are mainly associated with bedding planes, particularly those oriented N65-80 with slopes facing south and SSE, as well as NW-SE and NE-SW-trending fractures. Hydrological, tectonic, and anthropogenic factors also contribute to the instability.

Keywords: Road embankments; Gravity slides; Tectonics; Lithology; Shale; Tizi Ouadrene; External-Rif

1. Introduction

Landslides pose a risk to infrastructure and human safety, and can result in significant socio-economic losses (Dagorne et al., 2005; Devès et al., 2019; Gutiérrez-Martín et al., 2019; Anatole and Sébastien, 2022). They are influenced by natural factors such as geology, geometry, hydrology, climate, seismicity, as well as human activity (Martins-Campina, 2005; Gutiérrez-Martín et al., 2019). Road

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projects, in particular, are exposed to this risk due to the disruption of the natural equilibrium of slopes caused by earthworks (Martins-Campina, 2005; Yazidi, 2002).

This issue is even more acute in unstable geological contexts such as the Rif region located between Taza and Al Hoceima in northern Morocco. This region is characterized by geological and geomorphological complexity (El Gharbaoui, 1981; Poujol, 2014). It is included among active seismic and tectonically unstable zones (Charkaoui et al., 1990; Galindo-zaldivar et al., 2009; Hamdache et al., 2022). Several studies (Sossey Alaoui, 2005; Yazidi, 2002; Yazidi et al., 2017; Abidi et al. 2019; Cherifi et al., 2022a, 2022b) attest to the frequency of mass movements in this area. Moreover, the rapid expansion of the road infrastructure exacerbates the impact on this fragile environment and poses a major challenge for road projects in this zone, as evidenced by the case of the Tizi Ouadrene sector.

This sector is located approximately 68 kilometers northeast of Taza City, on the Taza-Al Hoceima expressway (Fig. 1). It lies within the Eastern Rif (Fig. 2). In this sector, the construction of the Taza-Al Hoceima expressway, has caused rotational, planar, and wedge landslides. Their triggering is mainly attributed to changes in the geometric and hydrological conditions of the site, as well as to the influence of other factors such as lithology, tectonics and the action of water. Furthermore, the area is characterized by a predominance of Cretaceous shales. However, it remains little studied, which further complicates risk management.



Fig.1. Situation Map Depicting the targeted study zone and the Tizi Ouadrene sector.

This manuscript examines the links between instabilities and lithological, tectonic, and geometric factors, along with the influence of water. The object of this work is to: i) define the lithological and petrographic characteristics of the Cretaceous shales in the study area. ii) Assess the combined impact of geological, hydrological, geometric, tectonic, and anthropogenic factors on the stability of cut slopes in shales. iii) Highlight the relationship between landslide types and the lithology they affect. iv) Analyze the influence of discontinuity planes and excavation plans on the configuration of landslides.

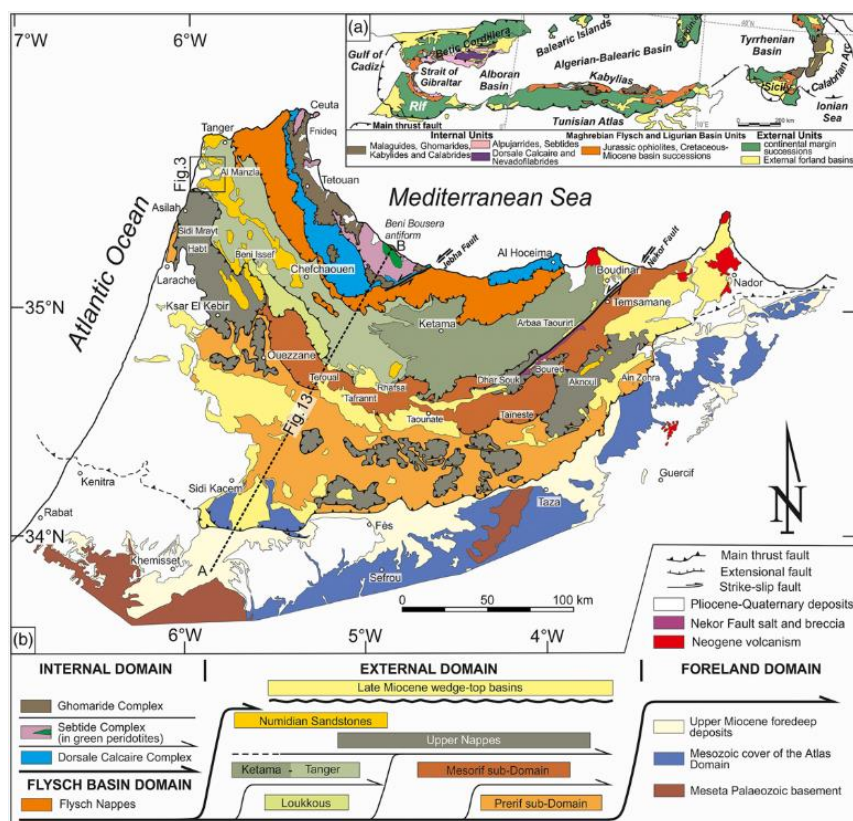


Fig.2. (a) Tectonic scheme of the Alpine chains in the western Mediterranean area (modified from Vitale & Ciarcia, 2013,). (b) Geological map of the Rif Chain (modified from Suter, 1980)

Our contribution aims to enrich the scientific literature with a view to building sustainable infrastructures in similar contexts, by providing relevant scientific data and analysis for appropriate design and execution.

2. Geological Context

The Rif is divided into crustal blocks separated by active faults, where the intra-Rif unit of Ketama-Tangier is thrust northwards by flysch nappes, and in turn, it thrusts southwards over Mesorif units (Andrieux, 1971). Rifian units or units of Intrarif origin, such as Aknoul, Bouhaddoud and Taïnesté, are completely allochthonous units that rest on the meso-Rif autochthonous basement and partly cover the internal Prérif in the External Rif, which was built up as a result of tectonic movements (folding and thrusting) that occurred during the Miocene (Chalouan et al., 2014). The Tizi Ouadrene sector is located in the southern part of the Eastern Rif (External Rif), falls within the Aknoul nappes (Fig. 2). This nappe is formed by allochthonous material (Frizon de Lamotte, 1981). It comprises shales and sandstones that transition towards the top to marls and pelites of Cretaceous age (Fig. 3). The latter are topped by a thick series of white flinty marlstones of Eocene-Oligocene age, which pass into Numidian sandstones of Aquitanian age, forming the termination of the Aknoul nappe series (Ennadifi, 1972; Leblanc, 1979; Pujol, 2014). The first was prior to diverticalisation, and the second after the nappe's departure. The two events are separated in time due to the development of horizontal veins with a beef structure (Frizon de Lamotte 1985).

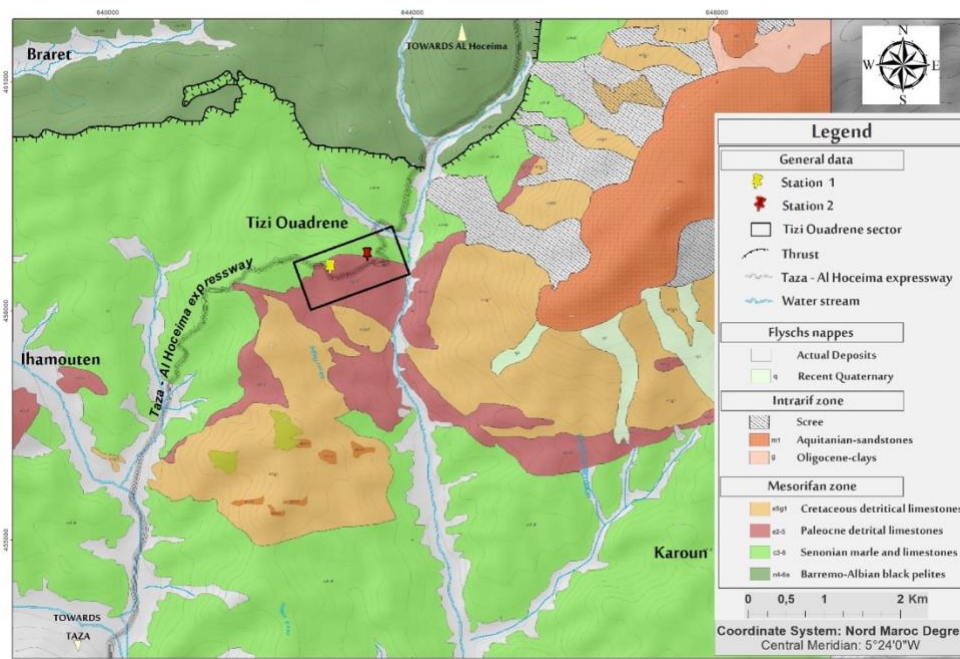


Fig.3. Detailed geological map of the study sector and area, with the locations of study stations.

Source: Geological Map of the Rif, Morocco, scale 1:50,000.

3. Materials and Methods

Our approach for understanding the factors contributing to landslide triggering on the embankments studied is based on field work, laboratory analysis and the use of computer-based methods.

To gather relevant data, we carried out fieldwork along the section of road studied. This data collection included geometric, lithological and structural characteristics in the area, particularly at our two study stations ST1 and ST2 (Fig. 3). In fact, we defined the geometric characteristics of the road embankments, carried out lithological observations consisting in the identification and description of meso-scale facies, and identified fault types and measured their directions and dips. We also took a dozen samples for petrographic and mineralogical studies. In the laboratory, we carried out in-depth analyses on the samples collected. We prepared polished sections and thin sections to study microstructures and identify mineralogical composition. The thin slides were observed and photographed using a polarizing microscope.

To process the field measurements and complete our study, we opted for the "Searchgrid" method (Galindo-Zaldivar and González Lodeiro, 1988). This approach enabled us to analyze and group by phase all the faults measured in particular at the two stations (ST1 and ST2). And to determine the orientation of the principal stresses ($\sigma_1 \geq \sigma_2 \geq \sigma_3$) as well as the axial ratio of the stress ellipsoid ($R = (\sigma_2 - \sigma_3) / (\sigma_1 - \sigma_3)$). Following, we carried out a kinematic analysis. This is a simple and recognized method for examining failures such as planar and wedge sliding (Hoek and Bray, 1981). To do this, we used Rocscience's Dips software, integrating all the families of discontinuities identified in the stations mentioned. The projection used (stereogram) is that of the lower hemisphere of the Schmidt canvas.

4. Results

4.1. Earthworks and Instability Triggering

The earthworks carried out to widen the existing road resulted in the creation of highly steep (inclinations of 66-85°) and high (approximately 12 m in height) road embankments (Fig. 4).

These changes removed major abutments at the base of the embankments and altered stormwater flow paths. As a result, this situation leads to landslides on road embankments, especially during rainy periods.

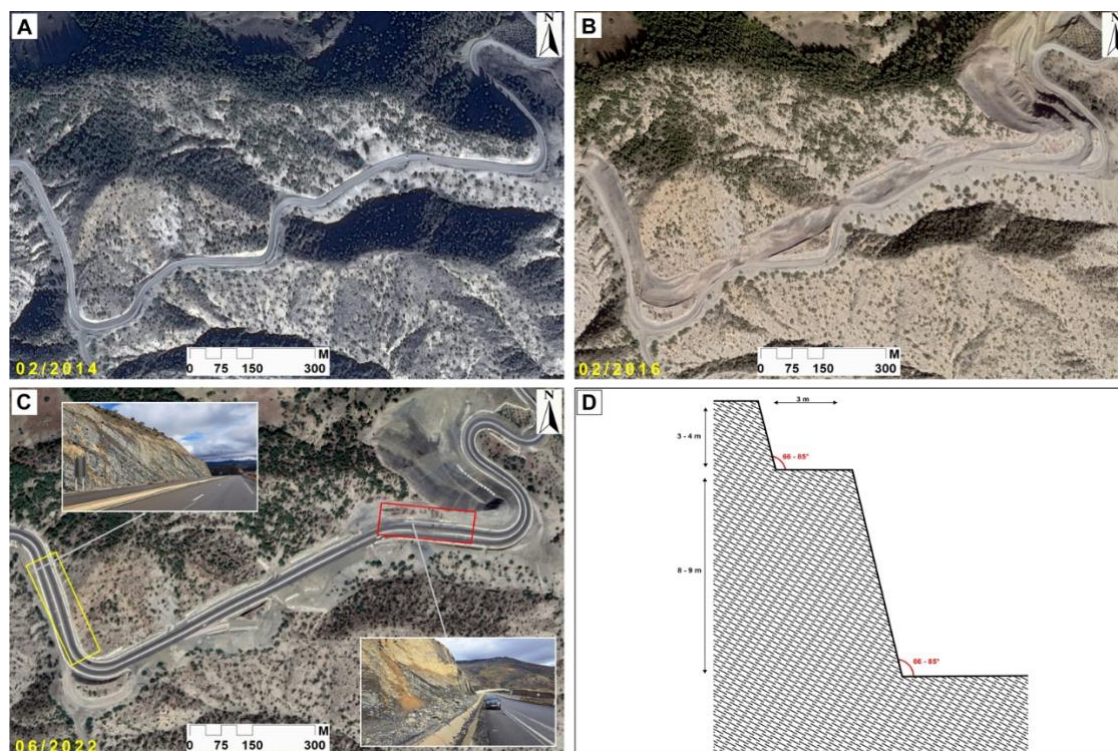


Fig.4. Anthropogenic action in the study sector. A, B and C: Google Earth satellite images (Altitude: 800m) of the study sector before, during and after earthworks, respectively. Yellow rectangle: ST1, red rectangle: ST2. D: Typical embankment cross-section.

Our field observations have revealed that these landslides are triggered in the form of planar, wedge, and rotational failures. Planar slides (Fig. 5A) and wedge slides (Fig. 5B) occur in stratified and fractured schist-limestone rocks. The striations are found to be important indicators of these types of slides (Fig. 5B). Planar failures specifically occur along flat surfaces parallel to the stratification. However, wedge failures are bounded by fractures creating angles within the rock masses. For rotational slides, they occur in formations predominantly composed of heavily crushed schist and are characterized by a tilting of the sliding mass downstream along a curved rupture surface (Fig. 5C).

Moreover, it is noteworthy that the slopes of station n°2 (ST2), oriented between N70 and N90 (~180°), are affected by planar and wedge failures of varying magnitudes, ranging up to approximately 25 meters in length, 5 to 7 meters in width, and 6 to 8 meters in height (Fig.5A and B). In contrast, the slopes of ST1, oriented between N150 and N170 (~230°), have generally remained intact (Fig. 4C).

4.2. Lithological and petrographic

The embankments reveal a lithology dominated by shales that are greyish to blackish and rarely yellowish when altered (Fig.6A). They are presented by alternating tabular benches of centimetric to decimetric thickness, sandwiching lenticular benches of decimetric strength of sandstone calcareous (Fig.6B) and blackish sandstone with millimetric beds of gypsum on the stratification and schistosity planes (Fig. 6C). The deposits at the base of the embankments are sound and compact, becoming increasingly altered towards the summit.



Fig.5. Types of landslides in the study sector. A wedge sliding at the intersection of two fractures (example: intersection of NE-SW and NW-SE faults). B- Planar sliding on stratified surfaces. C- Rotational sliding.

These deposits are cut into distinct blocks and panels by intense fracturing. Some of these fractures are filled with calcite (Fig. 6D). The petrographic study at the macroscopic scale has shown that these schists exhibit a laminated texture with a predominant blackish color and less frequent yellowish to greenish ones (Fig. 6E). The laminae are horizontal and rarely undulating, typically ranging from millimeter to centimeter thickness. These sheets are spaced apart and often show planes of weakness. The spaces between the laminae are locally occupied by thin whitish layers of gypsum (1 to 2 mm thick). The centimeter-thick facies are locally affected by fractures several centimeters long and millimeter-wide, partially or completely filled with calcite and iron oxides (Fig. 6F).

The microscopic analysis of the schistose facies reveals a superposition of light and dark laminae (Fig. 7A and B). The dark laminae are the most abundant, slightly undulating, coarsely lens-shaped, and affected by fractures filled with microsparite and sparite (Fig. 7 C and D). Their thickness ranges from 100 to 800 μm . Quartz grains and brownish micrite associated with organic matter and manganese oxides are the main components of these laminae.

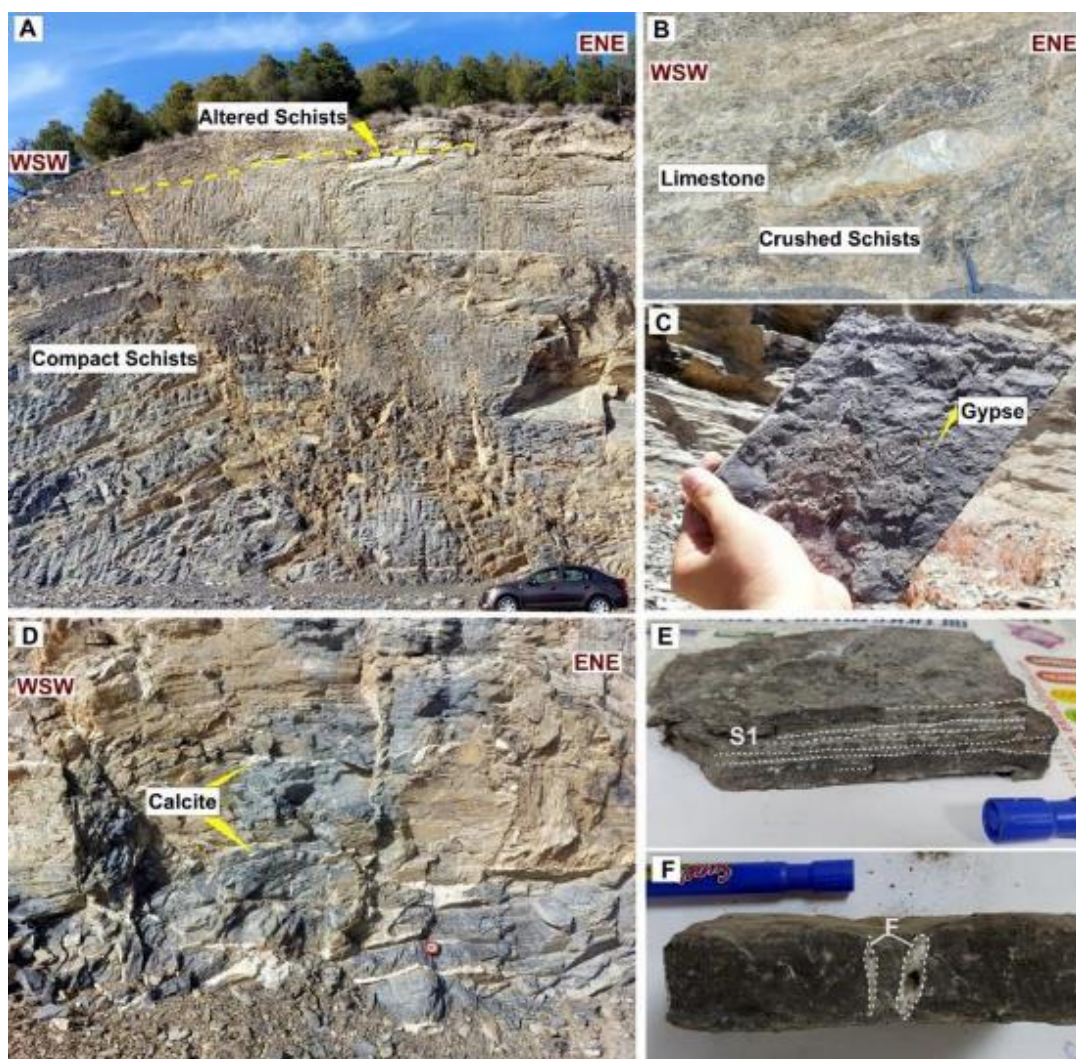


Fig.6. Lithological characteristics. A- Sound schists topped by weathered schists. B- Crushed schists with intercalated limestone lenses. C- Gypsum laminae in discontinuities (between schistose planes). D- Calcite veins in sound schists. E: Sample showing schistosity planes (S1). F: Sample showing cracks.

The light laminae are less abundant, slightly undulating, and have a thickness ranging from 200 to 700 μm . These laminae are formed by quartz grains packed within a microsparitic to sparitic matrix. In some areas, the dark laminae consist exclusively of manganese oxides, while the light laminae consist primarily of microsparite with very few quartz grains. The quartz grains exhibit a subangular to subrounded shape, with sizes ranging from approximately 50 to 300 μm , and their abundance varies from 15 to 20% of the total rock composition (Fig. 7A). These grains are either condensed within the light laminae or randomly dispersed within the micritic matrix of the dark laminae. In certain locations, these grains exhibit a slight alignment parallel to the schistosity plane. The entire space is completely filled with microsparitic to sparitic calcite (Fig. 7E and F). The spacing of the fractures and pores ranges from approximately 80 μm to 1 mm.

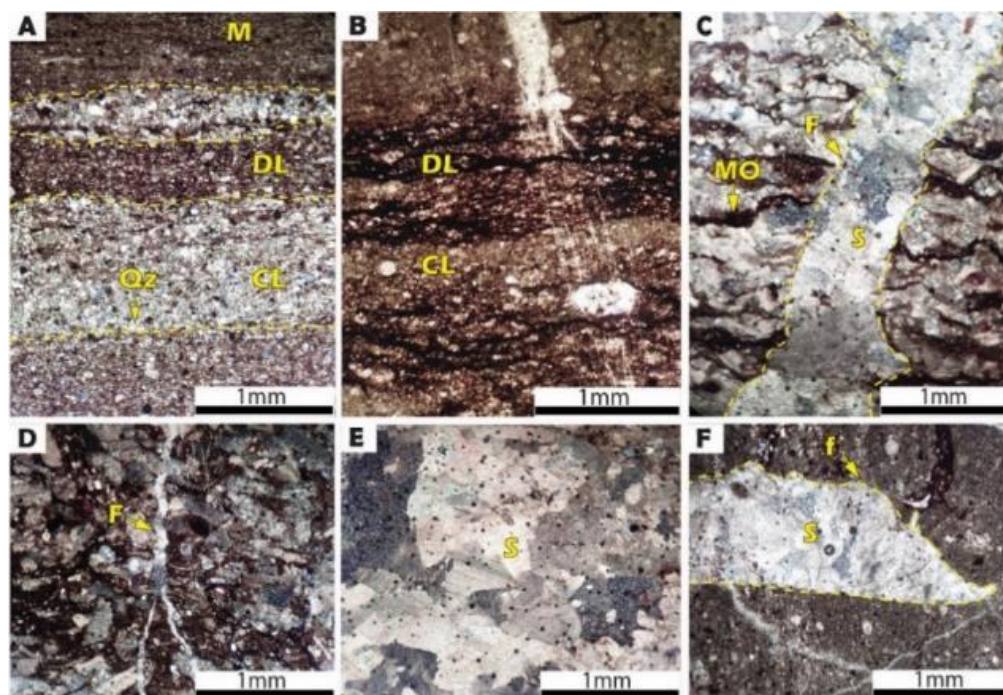


Fig.7. Microscopic view of the schistose facies of the Tizi Ouadrene. A et B- Alternation of light (CL) and dark (DL) laminate. C and D- fractures affecting the lamellae filled with sparite. E- Sparite in mosaics. f- Slot filled with sparite. F: fractures. D.L : Dark laminate, C.L : Clair laminate, M : Micrite, OM : Manganese oxide, V : Voide, F : Fente, Qz : Quartz, S : Sparite, MS : Microsparite.

4.3. Tectonic Studies

Our study area is highly fractured and tectonic activity, where we have conducted multiple measurements of faults (F) and diaclasses (D). Indeed, the shale formations with intercalations of calcareous and sandstone exposed at both stations (ST1 and ST2) are heavily fractured (Fig.8 and 9). They are affected by numerous normal and thrust faults with strike-slip components (sinistral or dextral), as well as X-shaped diaclasses (Fig. 8A).

The faults in these competent rock types are characterized by striated mirrors (Fig.8B and C), centimeter to decimeter-wide crushed zones and reddish to light brown fillings corresponding to a ferruginous crust. These faults are generally organized into two major families: F1, which runs ENE-WSW and is the most abundant, with dips varying between 65 and 85° to the north or south. So, F2, which runs NW-SE, with steep dips ranging from 75 to 87° to the SE or NW. The Slickenside fault planes show local recrystallizations of calcite and gypsum with several families of Slickensides (Fig.8D).

According to the work of Tahiri (1992), which explains that the system with cracking opposite to the direction of the applied stresses exhibits a more marked dilatation behavior than a system with cracking in the same direction as the applied stresses, we were able to discern this phenomenon in our study area and fully understand the instability anomaly of the ST1 and ST2 slopes. Diaclasses (D): are very frequent in the sector and easily identified by thin layers of iron oxides and secondary calcite fillings with millimeter to decameter spacing, directed perpendicularly or obliquely to the slope of the massif. They occur in two families (Fig. 8A): D1, N060-trending (NE-SW), subvertical or dipping slightly to the NW or SE; D2, running N110 to N130 (NW-SE) with subvertical dips dipping slightly to the NE or SW. Throughout the study sector, these two families of conjugate directions form an "X" shape (Fig. 8A). Consequently, we have deduced that these diaclasses are subject to a stress field with a σ_1 NNE-SSW to N-S-trending.

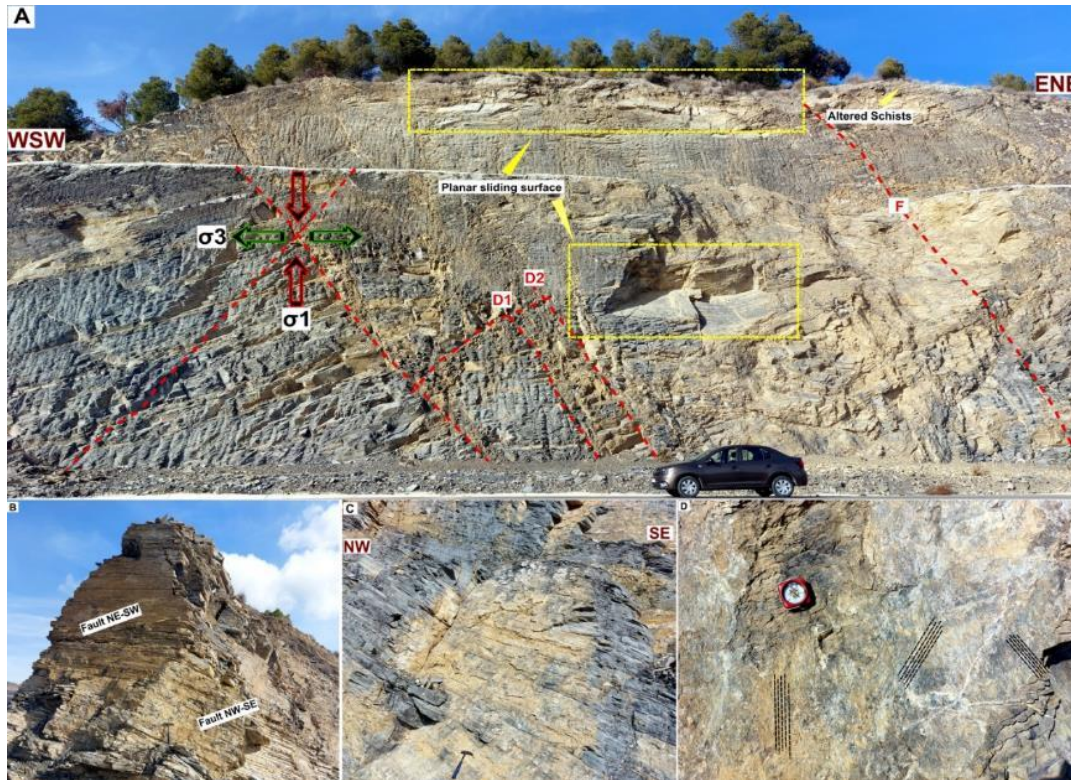


Fig.8. Fracture characteristics. A- Fault plane, diaclasses (D1 and D2) and stress fields σ_1 and σ_3 . B and C- Striated fault mirrors (NE-SW and NW-SE). D- Fault mirror showing calcite and iron oxides with several families of striations.

Schistosity (S1): consists of thin, sometimes wavy or irregular sheets arranged along planes. These planes divide into two perpendicular families, giving the shale a friable aspect. The planes are visible at millimeter spacing and are divided into two families: one oriented ESE-WNW with a dip of 67° to 90° , and the other oriented NE-SW with a dip of 70° to 85° . This configuration is indicative of anastomosing deformation in a coaxial environment, visible in the terrain in the form of parallelepiped blocks (Fig. 9C).

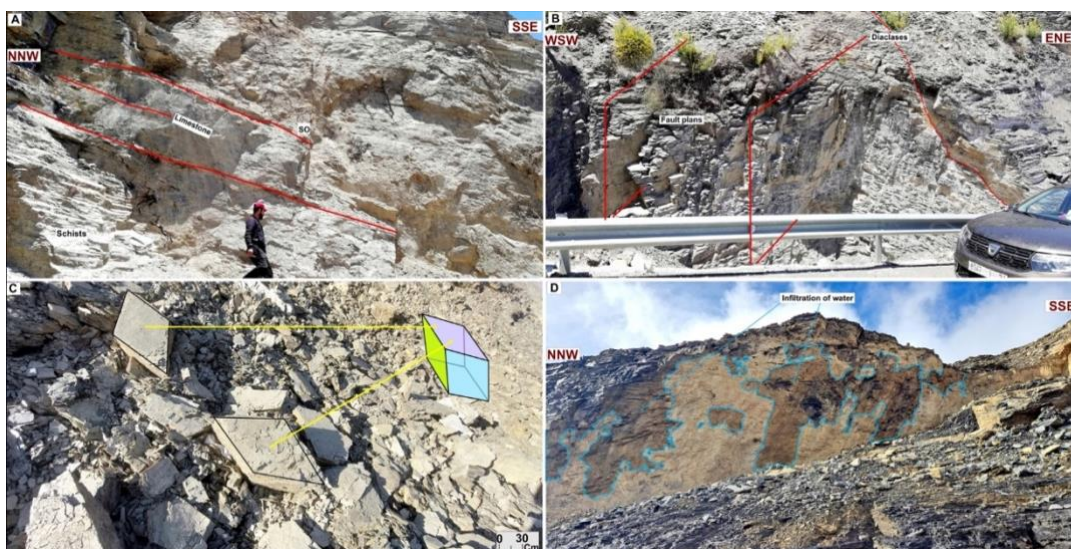


Fig.9. Field photos showing examples of discontinuities. A- stratification (S0). B- faults and diaclasses. C- Parallelepiped blocks. D- Water infiltration through discontinuities.

Stratification (S0): The formations described in the lithological analysis show overall large-scale tilts and rare small-scale undulations. All benches are oriented N70 to N90, with an overall dip to the south and south-east, varying between 15° and 30° and exceeding 45° in the vicinity of faults (Fig. 9A). The planes in the sector are homogeneous, dipping parallel to the slope of the ST2 road embankments and perpendicular to the ST1 road embankments.

4.4. Computer Processing

4.4.1. Using the "Search-Grid" method

The analysis of faults measured in the terrain using the "Search-Grid" method (Galindo-Zaldivar and González Lodeiro, 1988), provided information on the orientation of the principal stresses σ_1 , σ_2 , and σ_3 ($\sigma_1 \geq \sigma_2 \geq \sigma_3$) and the axial ratio of the stress ellipsoid ($R = (\sigma_2 - \sigma_3) / (\sigma_1 - \sigma_3)$). The results are summarized in Table 1 and Figure 10. The analysis of the faults in two sectors, ST1 and ST2, has revealed that the Tizi Ouadrene region is tectonically unstable (Table1).

Table 1. Search-Grid analysis results for ST1 and ST2.

Phases	Stress ellipsoid			Axial ratio($R = (\sigma_2 - \sigma_3) / (\sigma_1 - \sigma_3)$)	Type of ellipsoid
	σ_1	σ_2	σ_3		
Phase ST1	N126 PL 24	N285 PL65	N32 PL08	$R = 0.01$	Oblate
Phase ST2	N 323 PL08	N67 PL 60	N 228 PL 29	$R = 0.42$	Intermediate

We can see from Table 1, that we have only one deformation phase. The result of the "Search-Grid" processing of ST1 is an axial ratio value ($R=0.01$) showing a prolate stress ellipsoid. The most significant orientation is that of the $\sigma_1=N126$ Pl 24 axis, since the σ_3 and σ_2 axes have close values. So, the zone is undergoing NW-SE compression (Table1, Fig.10A). For station ST2, the value of the axial ratio is $R=0.42$, so the stress ellipsoid is of the intermediate type. The σ_1 (N 323 PL08) and σ_3 (N228 PL29) axes are sub horizontal. This station (ST2) has two stress fields, one compressive NW-SE and a second extensive NE-SW. This station reveals a NW-SE compression (Table1, Fig. 10B) comparable to that of station ST1, and a NE-SW extension that clearly confirms the existence of a current movement of station ST2 to the south.

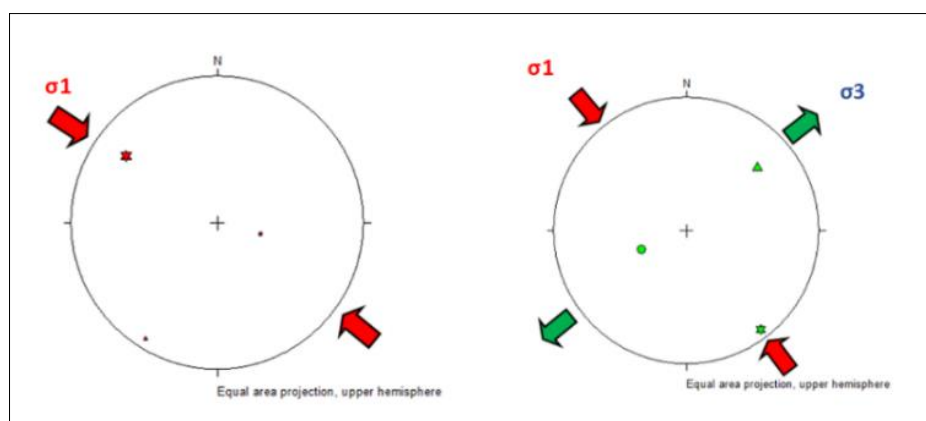


Fig.10. A: Stereographic presentation σ_1 , σ_2 , & σ_3 of oblate stress ellipsoid ($R=0.99$) at station ST1.

B: Stereographic presentation of σ_1 , σ_2 , & σ_3 intermediate stress ellipsoid ($R= 0.42$) at station ST2

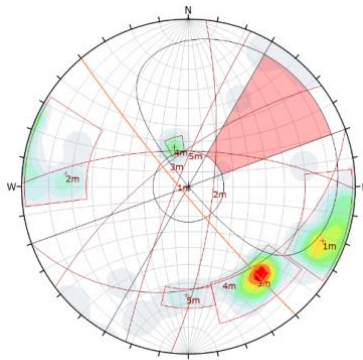
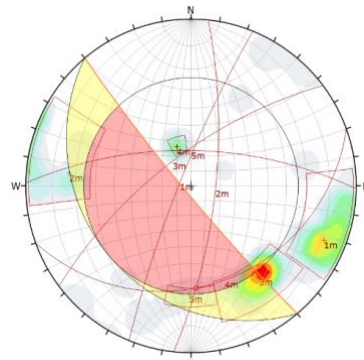
4.4.2. Kinematics analysis

Kinematic analysis is an important tool for studying the stability of fractured rock slopes. Using Rocscience's Dips software, we carried out this analysis, which consisted of a stereographic projection

(lower hemisphere) of all the discontinuities (sedimentary joints, faults, diaclasses and schistosity) surveyed in stations ST1 and ST2, followed by an assessment of their potential for planar and wedge slipping. The road embankments at these stations are principally composed of indurated shale, with a maximum inclination of around 85°. In ST1, they are oriented 230° perpendicular to the dip of the S0, while in ST2 they are oriented 180° parallel to the dip of the S0 (Fig. 4C).

Stereographic projection enabled us to distinguish 05 main families of discontinuities in ST1 and 07 in ST2. The results of the analysis show that Planar sliding has a critical index of 5% in ST1 and 100% in ST2. For Wedge sliding, the critical index obtained is 10% in station ST1 and 29% in station ST2 (Tables 2 and 3).

Table 2. Kinematic analysis results in ST1

Slop dip	Slop dip direct.	Excavation direction	Planar sliding	Wedge sliding																																																																																														
85°	230°	N75	<table><thead><tr><th>Color</th><th>Density Concentrations</th></tr></thead><tbody><tr><td></td><td>0.00 - 1.70</td></tr><tr><td></td><td>1.70 - 3.40</td></tr><tr><td></td><td>3.40 - 5.10</td></tr><tr><td></td><td>5.10 - 6.80</td></tr><tr><td></td><td>6.80 - 8.50</td></tr><tr><td></td><td>8.50 - 10.20</td></tr><tr><td></td><td>10.20 - 11.90</td></tr><tr><td></td><td>11.90 - 13.60</td></tr><tr><td></td><td>13.60 - 15.30</td></tr><tr><td></td><td>15.30 - 17.00</td></tr></tbody></table><table><thead><tr><th>Contour Data</th><th>Pole Vectors</th></tr></thead><tbody><tr><td>Maximum Density</td><td>16.69%</td></tr><tr><td>Contour Distribution</td><td>Fisher</td></tr><tr><td>Counting Circle Size</td><td>1.0%</td></tr></tbody></table><table><thead><tr><th>Kinematic Analysis</th><th>Planar Sliding</th></tr></thead><tbody><tr><td>Slope Dip</td><td>85</td></tr><tr><td>Slope Dip Direction</td><td>230</td></tr><tr><td>Friction Angle</td><td>24°</td></tr><tr><td>Lateral Limits</td><td>20°</td></tr></tbody></table><table><thead><tr><th></th><th>Critical</th><th>Total</th><th>%</th></tr></thead><tbody><tr><td>Planar Sliding (All)</td><td>2</td><td>39</td><td>5.13%</td></tr></tbody></table>	Color	Density Concentrations		0.00 - 1.70		1.70 - 3.40		3.40 - 5.10		5.10 - 6.80		6.80 - 8.50		8.50 - 10.20		10.20 - 11.90		11.90 - 13.60		13.60 - 15.30		15.30 - 17.00	Contour Data	Pole Vectors	Maximum Density	16.69%	Contour Distribution	Fisher	Counting Circle Size	1.0%	Kinematic Analysis	Planar Sliding	Slope Dip	85	Slope Dip Direction	230	Friction Angle	24°	Lateral Limits	20°		Critical	Total	%	Planar Sliding (All)	2	39	5.13%	<table><thead><tr><th>Color</th><th>Density Concentrations</th></tr></thead><tbody><tr><td></td><td>0.00 - 1.70</td></tr><tr><td></td><td>1.70 - 3.40</td></tr><tr><td></td><td>3.40 - 5.10</td></tr><tr><td></td><td>5.10 - 6.80</td></tr><tr><td></td><td>6.80 - 8.50</td></tr><tr><td></td><td>8.50 - 10.20</td></tr><tr><td></td><td>10.20 - 11.90</td></tr><tr><td></td><td>11.90 - 13.60</td></tr><tr><td></td><td>13.60 - 15.30</td></tr><tr><td></td><td>15.30 - 17.00</td></tr></tbody></table><table><thead><tr><th>Contour Data</th><th>Pole Vectors</th></tr></thead><tbody><tr><td>Maximum Density</td><td>16.69%</td></tr><tr><td>Contour Distribution</td><td>Fisher</td></tr><tr><td>Counting Circle Size</td><td>1.0%</td></tr></tbody></table><table><thead><tr><th>Kinematic Analysis</th><th>Wedge Sliding</th></tr></thead><tbody><tr><td>Slope Dip</td><td>85</td></tr><tr><td>Slope Dip Direction</td><td>230</td></tr><tr><td>Friction Angle</td><td>24°</td></tr></tbody></table><table><thead><tr><th></th><th>Critical</th><th>Total</th><th>%</th></tr></thead><tbody><tr><td>Wedge Sliding</td><td>1</td><td>10</td><td>10.00%</td></tr></tbody></table>	Color	Density Concentrations		0.00 - 1.70		1.70 - 3.40		3.40 - 5.10		5.10 - 6.80		6.80 - 8.50		8.50 - 10.20		10.20 - 11.90		11.90 - 13.60		13.60 - 15.30		15.30 - 17.00	Contour Data	Pole Vectors	Maximum Density	16.69%	Contour Distribution	Fisher	Counting Circle Size	1.0%	Kinematic Analysis	Wedge Sliding	Slope Dip	85	Slope Dip Direction	230	Friction Angle	24°		Critical	Total	%	Wedge Sliding	1	10	10.00%
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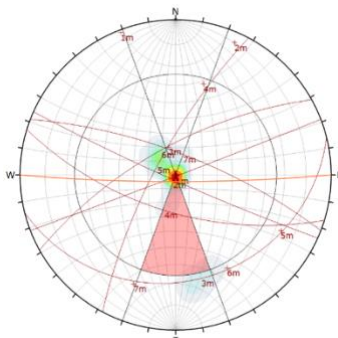
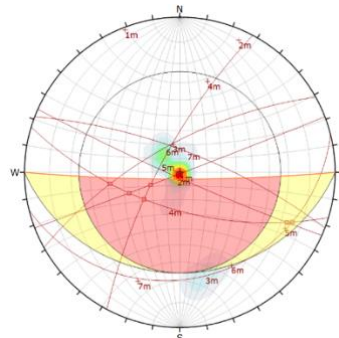
5. Discussions

The Tizi Oudarene sector is located in the Rif region of northern Morocco, renowned for its vulnerability to movements of land, and its seismic and tectonic activity. This sector is mainly characterized by a predominance of shale, which are marked by instability due to their anisotropy and mechanical vulnerability (Wittke, 2014, Cherifi, 2022a). In addition, recent human intervention, in particular earthworks carried out to build the road (Fig. 4), has also contributed to the instability of the sector by altering its original geometric and hydrological conditions. This unstable geological and geotechnical context has favored the appearance of landslides on road embankments.

Fracturing and microscopic analysis have shown that the shale formations outcropping in the sector are affected by various discontinuities of different origins. The stereographic projection distinguishes 05 main families of discontinuities in ST1 (Table 2) and 07 in ST2 (Table 3). Discontinuities are zones

of fragility due to their mechanical properties, such as tensile strength and shear strength, which are inferior to those of the rock matrix (Martin and Saïta, 2012). they cut rocky massifs into blocks that can slide in the direction of slope excavation. This indicates their important role in the instability triggered in the sector.

Table 3. Kinematic analysis results in ST2

Slop dip	Slop dip direct.	Excavation direction	Planar sliding	Wedge sliding																																																																																																																													
85°	180°	N130	<table><tr><th>Color</th><th>Density Concentrations</th></tr><tr><td></td><td>0.00 - 3.30</td></tr><tr><td></td><td>3.30 - 6.60</td></tr><tr><td></td><td>6.60 - 9.90</td></tr><tr><td></td><td>9.90 - 13.20</td></tr><tr><td></td><td>13.20 - 16.50</td></tr><tr><td></td><td>16.50 - 19.80</td></tr><tr><td></td><td>19.80 - 23.10</td></tr><tr><td></td><td>23.10 - 26.40</td></tr><tr><td></td><td>26.40 - 29.70</td></tr><tr><td></td><td>29.70 - 33.00</td></tr></table><table><tr><th colspan="2">Contour Data</th><th>Dip Vectors</th></tr><tr><td colspan="2">Maximum Density</td><td>32.31%</td></tr><tr><td colspan="2">Contour Distribution</td><td>Fisher</td></tr><tr><td colspan="2">Counting Circle Size</td><td>1.0%</td></tr></table><table><tr><th colspan="2">Kinematic Analysis</th><th>Planar Sliding</th></tr><tr><td colspan="2">Slope Dip</td><td>85</td></tr><tr><td colspan="2">Slope Dip Direction</td><td>180</td></tr><tr><td colspan="2">Friction Angle</td><td>24°</td></tr><tr><td colspan="2">Lateral Limits</td><td>20°</td></tr><tr><td></td><td></td><td>Critical</td><td>Total</td><td>%</td></tr><tr><td></td><td>Planar Sliding (All)</td><td>4</td><td>34</td><td>11.76%</td></tr><tr><td></td><td>Planar Sliding (Set 3)</td><td>1</td><td>5</td><td>20.00%</td></tr><tr><td></td><td>Planar Sliding (Set 4)</td><td>2</td><td>2</td><td>100.00%</td></tr></table>	Color	Density Concentrations		0.00 - 3.30		3.30 - 6.60		6.60 - 9.90		9.90 - 13.20		13.20 - 16.50		16.50 - 19.80		19.80 - 23.10		23.10 - 26.40		26.40 - 29.70		29.70 - 33.00	Contour Data		Dip Vectors	Maximum Density		32.31%	Contour Distribution		Fisher	Counting Circle Size		1.0%	Kinematic Analysis		Planar Sliding	Slope Dip		85	Slope Dip Direction		180	Friction Angle		24°	Lateral Limits		20°			Critical	Total	%		Planar Sliding (All)	4	34	11.76%		Planar Sliding (Set 3)	1	5	20.00%		Planar Sliding (Set 4)	2	2	100.00%	<table><tr><th>Color</th><th>Density Concentrations</th></tr><tr><td></td><td>0.00 - 3.30</td></tr><tr><td></td><td>3.30 - 6.60</td></tr><tr><td></td><td>6.60 - 9.90</td></tr><tr><td></td><td>9.90 - 13.20</td></tr><tr><td></td><td>13.20 - 16.50</td></tr><tr><td></td><td>16.50 - 19.80</td></tr><tr><td></td><td>19.80 - 23.10</td></tr><tr><td></td><td>23.10 - 26.40</td></tr><tr><td></td><td>26.40 - 29.70</td></tr><tr><td></td><td>29.70 - 33.00</td></tr></table><table><tr><th colspan="2">Contour Data</th><th>Dip Vectors</th></tr><tr><td colspan="2">Maximum Density</td><td>32.31%</td></tr><tr><td colspan="2">Contour Distribution</td><td>Fisher</td></tr><tr><td colspan="2">Counting Circle Size</td><td>1.0%</td></tr></table><table><tr><th colspan="2">Kinematic Analysis</th><th>Wedge Sliding</th></tr><tr><td colspan="2">Slope Dip</td><td>85</td></tr><tr><td colspan="2">Slope Dip Direction</td><td>180</td></tr><tr><td colspan="2">Friction Angle</td><td>24°</td></tr><tr><td></td><td></td><td>Critical</td><td>Total</td><td>%</td></tr><tr><td></td><td>Wedge Sliding</td><td>6</td><td>21</td><td>28.57%</td></tr></table>	Color	Density Concentrations		0.00 - 3.30		3.30 - 6.60		6.60 - 9.90		9.90 - 13.20		13.20 - 16.50		16.50 - 19.80		19.80 - 23.10		23.10 - 26.40		26.40 - 29.70		29.70 - 33.00	Contour Data		Dip Vectors	Maximum Density		32.31%	Contour Distribution		Fisher	Counting Circle Size		1.0%	Kinematic Analysis		Wedge Sliding	Slope Dip		85	Slope Dip Direction		180	Friction Angle		24°			Critical	Total	%		Wedge Sliding	6	21	28.57%
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Additionally, the discontinuities promote the infiltration and circulation of runoff water in the shales (Fig. 9D). The presence of water promotes mechanical erosion (Sissakian, 2022), and the dissolution of binding minerals such as gypsum and calcite, which are present in high concentrations in the shales studied. This leads to a reduction in shear strength (Sha, 2016; Sun, 2020), and when shear stresses exceed the rock's shear strength, instability becomes certain (Gao, 2017; Kolapo et al., 2022). The mechanical and chemical action of water therefore plays a major role in shale instability. This hypothesis is confirmed by the recurrent observation of landslide triggering in the sector during each rainy episode, as well as by the results of other studies, such as that conducted by Gutiérrez-Martín (2019).

Field observations have shown that landslides are particularly active on the embankments of station ST1, occurring in planar and wedges slides. They are less pronounced at station ST2. The embankments of ST1 and ST2 share similar characteristics in terms of slope (70°-79°) and lithological nature (indurated schists), but differ in orientation. In ST1, they are oriented between N75 and N100, sloping steeply to the south and southeast and in a direction perpendicular to the dip of the S0, whereas in ST2, they are oriented from NW to SE in a direction parallel to the dip of the S0 (Fig. 4). These observations underline the importance of embankments orientation in relation to the dip of the geological strata, in triggering and shaping the landslides affecting the embankments in our sector.

The analysis of the faults at the two stations (ST1 and ST2) using the "Search-Grid" method showed that they are tectonically unstable (Table1, Fig. 10). Indeed, the ST1 zone shows a Prolate stress ellipsoid

and a compressive stress field-oriented NW-SE, while the ST2 zone reveals an intermediate stress ellipsoid and two stress fields: one compressive σ_1 , NW-SE-trending and the other σ_3 extensive NE-SW (Table 1, Fig. 10). Thus, the "X"-shaped diaclases show a generally NNE-SSW stress field. These results confirm the existence of a current southward displacement of the ST2. While the results of the ST1 treatment also point to future embankments instability. The contribution of faults and diaclases studies further explains the instability at both stations.

In addition, the results of the kinematic analysis (Tables 2 and 3) showed that Wedges sliding are triggered when discontinuities intersect the slope excavation plane. This risk is high if the slope is parallel to the S0 stratification. This is the case for ST2 slopes, with a critical index of 29%, compared with 10% for ST1 slopes. However, planar landslides are mainly linked to the dip of the S0 stratification in relation to that of the slope, with a high risk in the case of parallel orientations. This is the case for ST2 slopes, where the critical index obtained exceeds 100%, compared with 5% for ST1 slopes. According to the above, slope stability and their failure modes are strongly controlled by the intersection of discontinuities, and by their orientations relative to those of the slopes. This conclusion is consistent with previous work (Hoek, 1990; Demay and Person, 1998; Goodman, 2000; Azeze, 2020; Metya, 2021; Kamil, 2021; Al-Samarrai, 2022).

Finally, it should be pointed out, that improving slope stability can be achieved with reinforcement devices such as bolts and anchor cables or nailed walls (Kolapo et al., 2022). Palliative measures, such as efficient drainage systems and the use of clad wire mesh, can also be considered to contain ground movement.

6. Conclusions

The results of this study underline the importance of considering the vulnerability of Cretaceous shales, which are widely distributed in the northern regions of Morocco.

The observed instability of the studied road slopes results from the interaction of various factors, including litho-structural and geomorphological characteristics as predisposing factors, anthropogenic actions as triggering factors, and hydraulic influences that play both roles simultaneously. It is therefore crucial to take all these factors into account when designing road projects. In-depth geological and tectonics studies, including the characterization of discontinuities and the dip of geological strata, are essential to effectively adapt the orientation of the embankments.

Furthermore, this study opens up promising new perspectives for the geomechanically characterization of the investigated shales. The objective is to estimate shear parameters, which are difficult to obtain for shales using conventional geotechnical methods. These data hold crucial importance for numerical modeling, which plays an essential role in analyzing slope stability and assessing the impact of reinforcement systems with a view to minimizing them.

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