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Original Article

Stability of Fractured Rock Massifs: Geotechnical Characterization: Case of the Excavation N°11 of the Taza-Al Hoceima Expressway in Bouârma. (Al Hoceima, Northern Morocco)

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Abstract *- This article examines the geotechnical behavior of rock masses, emphasizing the role of discontinuities and the critical assessment of rock joints, which significantly influence the overall stability of the massif. The study focuses on several unstable sections of the Taza-Al Hoceima expressway in the Moroccan Rif mountains, an area notorious for landslide and rockfall risks. To quantitatively assess stability and better understand the rock massif's behavior, numerical modeling is conducted using the Joint Rock module specifically designed for discontinuous environments. This modeling simulates complex interactions between an intact rock and identified discontinuities, revealing potential weakness zones and sliding risks, particularly in unfavorable sections. In conclusion, this research highlights the necessity of a multidisciplinary approach that integrates geology, geotechnics, and numerical modeling for engineering projects in complex geological contexts characterized by high mechanical anisotropy. These findings contribute significantly to enhancing safety measures and informing design strategies in geotechnically challenging environments.*

Keywords *- Stability, Geology, Risk, Rocky behavior, Numerical modeling.*

1. Introduction

The stability of fractured rock slopes represents one of the most complex challenges in geotechnical engineering, particularly in mountainous regions where the risks of landslides and rockfalls can have disastrous consequences. Unlike continuous, homogenous, and isotropic media, discontinuity is one of the most significant parameters influencing rock mass strength, posing various challenges [1]. These discontinuities play a crucial role in the stability of rock masses, which is especially relevant in the context of road projects.

Indeed, the stability of rock masses depends not only on the nature of the in-situ ground but also on the fracturing network, characterized by its roughness, joint nature, density, and the arrangement of discontinuities relative to the slope faces. Thus, understanding and predicting the behavior of rock masses under various conditions and technical constraints is critical for ensuring the safety of infrastructure, particularly in the domain of rock mass classification [2]. This is particularly true for projects planned in mountainous regions dominated by fractured rocks (Figure 1), such as in the Moroccan Rif, where the geology presents heavily folded geological structures with large-scale thrust sheets [3].

Fig. 1 Fractured rock, the rif mountains, morocco

The mountains in this region, characterized by a very rugged relief, rank among the areas most severely affected by problems such as the destruction of housing, loss of agricultural land, and degradation of infrastructure, including roads, railways, and bridges [4].

For instance, the photo below illustrates a typical case of rock slope instability in northern Morocco (Figure 2). This collapse necessitated the diversion of the RR607 road connecting the city of Berkane to the Fes-Oujda highway, thereby disrupting traffic and leading to the relocation of homes situated at the top of the slope.

Fig. 2 Instability of a rocky slope in northern morocco; the road has been diverted due to these instabilities

In the face of these challenges, traditional rock slope stability analyses relied primarily on empirical methods and field observations. However, with technological advancements and the development of powerful computational tools, numerical modeling has become essential for evaluating and predicting the stability of rock structures with greater precision and reliability.

The case study focuses on several sections of highly tectonized schists, raising numerous instability issues encountered along almost the entire route of the "Taza-Al Hoceima" expressway project in northern Morocco. In this context, the work aims to model these discontinuous rock structures and present a qualitative and preventive assessment of unstable zones, thereby contributing to the safety and sustainability of infrastructure in the region.

Thus, compared to previous works, the study aims to develop a rigorous methodology for predicting the stability of these structures, taking into account the specificities of discontinuous media and relying on the examination of practical cases of observed instabilities: lithology, direction, dip of the layers, orientation of the route, and geotechnical characteristics of the rock masses.

2. Material and Methods

2.1. Methodology

The diversity of instability and failure mechanisms within rock masses indicates that it is illusory to rely on a single method for assessing their stability [5]. Indeed, several methods, varying in complexity, are available for this evaluation.

Among the classical approaches, geological and geomechanical analysis, which relies on direct observation and interpretation of lithological features and geological structures, proves particularly significant. This method is based on an integrated analysis of several key parameters:

Identification of discontinuity types: Discontinuities may include fractures, joints, faults, and slip planes. Characterizing these elements, along with their orientation, is essential as they directly influence the stability of slopes.

Configuration analysis: The geometric arrangement of discontinuities affects how forces are transmitted within the rock mass. Understanding this configuration (angle, spacing, and interconnection) is fundamental for evaluating potential weakness zones.

Assessment of mechanical properties: This characterization includes analyzing the mechanical properties of discontinuity surfaces, such as strength, friction angle, and cohesion, which are crucial for understanding the slope's capacity to resist failure.

Environmental influence: Discontinuity networks can be affected by environmental factors such as water and erosion, which significantly impact the long-term strength of the rock mass.

Among the critical in situ characteristics for a correct stability analysis, the following can be found:

- Lithology: This determines the mechanical properties of materials, directly influencing strength, deformation under load, and the evolution of characteristics over the long term.
- Discontinuities: These critical zones can serve as sliding paths. It is essential to identify their type and behavior to assess their impact on the integrity of the mass and predict failure mechanisms.
- Orientation and dip of the discontinuities: These factors influence stress distribution within the mass. Discontinuities oriented in the direction of the slope can decrease cohesion and increase the risk of failures. In fact, a highly inclined discontinuity is particularly susceptible to failure, especially when subjected to external loads or water variations.
- Thickness and nature of the joints: Evaluating the thickness and nature of rock joints facilitates estimating the contact area and overall strength of rock masses.

Other methods, such as numerical modeling, enable the simulation of various loading scenarios and environmental conditions. These modern tools enhance the understanding of interactions within rock masses and deformation mechanisms while allowing for reliable and efficient reproduction of local discontinuous behavior and the overall response of the structure [6]. However, their effectiveness depends on the quality of in situ data and the accuracy of the assumptions made.

Moreover, numerical modeling also incorporates the analysis of the response of roadway slopes. The model's accuracy depends on the proper characterization of discontinuities acting as sliding zones to simulate loading conditions, resistance, and interactions within the mass accurately.

In the context of our study on the instabilities observed on the slopes of the Taza-Al-Hoceima expressway, numerical modeling will be conducted using the Jointed Rock Model (JR). The results will be verified and compared with observations and findings of instabilities on-site for the various analyzed areas. The Jointed Rock model is a perfectly elastic and anisotropic material model designed to simulate the behavior of jointed rocks. It incorporates intact rock and up to three principal directions of joints (slip planes), thus facilitating the representation of transverse anisotropy and variable strength properties according to Coulomb's criterion.

This model simulates complex behaviours in jointed rock masses during geotechnical engineering analyses. The principles of this model are detailed further on. Finally, it is crucial to recognize that each method has specific application areas. Furthermore, integrating multiple approaches can provide a more comprehensive and accurate assessment of the stability of rock masses.

The methodology followed for the stability analysis of the studied areas is illustrated in the graph in Figure 3.

2.2. Parameters for Assessing Rock Masses

Field measurements and investigations allow for extracting a set of parameters and indices that characterize the quality and stability of rock masses.

RQD: It represents the percentage of intact and sound rock extracted from a borehole, regardless of its orientation [7]. It is calculated by taking the ratio of the total length of intact and sound core pieces at least 100 mm long to the total length of the core.

Bieniawski introduced a rock mass classification known as the Geomechanics Classification or the Rock Mass Rating (RMR) system [8]. The classification of a rock mass using the RMR system is based on the following six parameters:

- Uniaxial Compressive Strength of the rock material (UCS).
- Rock Quality Designation (RQD).
- Spacing of discontinuities.
- Condition of discontinuities.
- Groundwater conditions.
- Orientation of discontinuities.

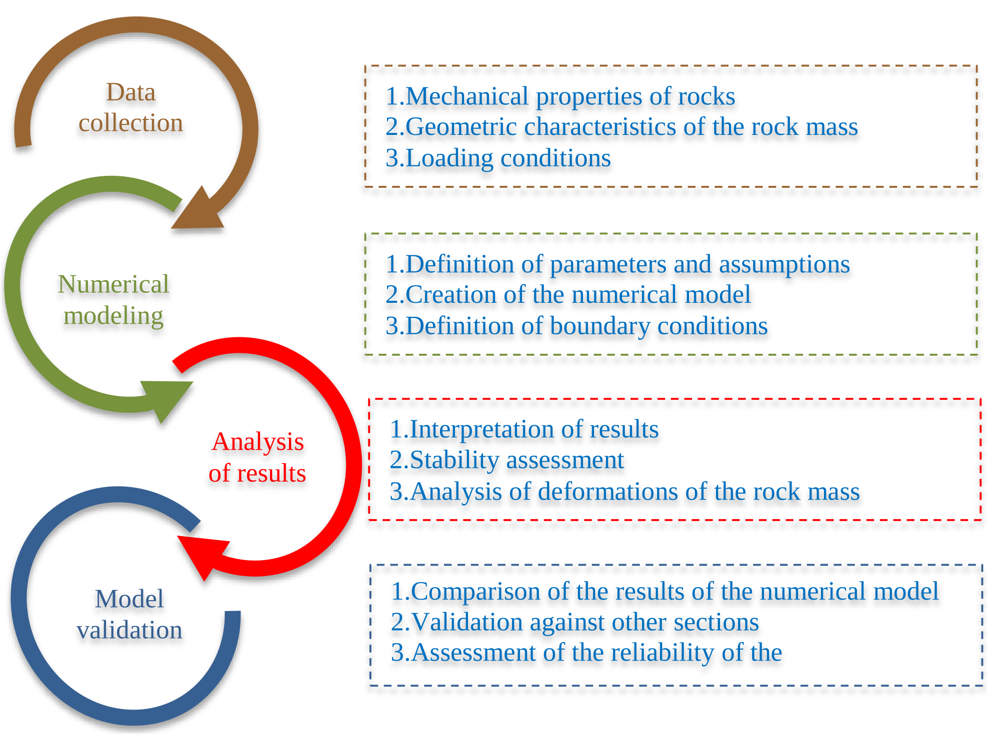

Fig. 3 Methodology adopted for stability assessment

Hoek proposed the Geological Strength Index (GSI), which, when combined with the properties of intact rock, allows for evaluating the reduction in rock mass strength under various geological conditions [9]. Thus, according to

Hoek and Brown, the deformation modulus is assessed based on the GSI index and the compressive strength as follows [10].:

$$EM(GPa) = \frac{\sqrt{\text{UCS(MPa)}}}{100} * 10^{(GSI-10/40)}$$

2.3. Results of Site Investigations

The instability sections studied are located on the Taza – Al Hoceima expressway in the Driouch province. The satellite image in Figure 4 illustrates the location of the studied unstable areas:

Fig. 4 Location of the unstable sections on the Taza-Al Hoceima expressway

In these areas, the road is hilly and winding with sometimes very tight bends; these are areas characterized by uneven terrain. The road is hilly and winding in these areas, with sometimes very tight turns; these zones are characterized by rugged terrain. Geologically, the study area belongs to the mesorifain units, which correspond to an interleaving of rocks from the Jurassic to the lower Cretaceous age, with the stacking occurring before the Oligocene [11]. Below is an excerpt from the Rif structural map and a geological cross-section traversing the study area, which aptly illustrate the geological complexity of the Moroccan Rif region [12].

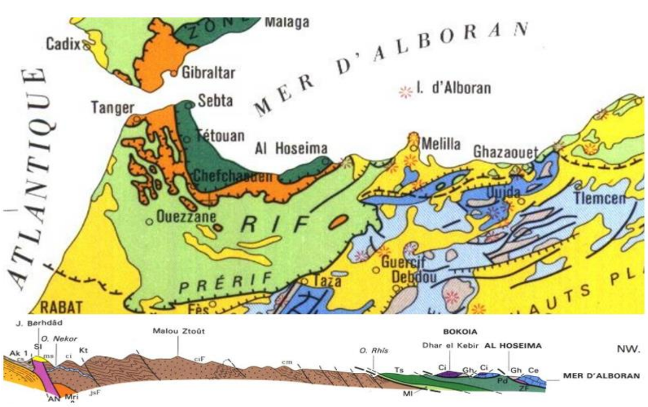

Fig. 5 The structural map of the Rif chain according to G. Suter, 1977

On-site observations of the freshly cut formations during excavations indicate that the studied area primarily comprises schists, marly schists, marls, and quartzites (Figure 5).

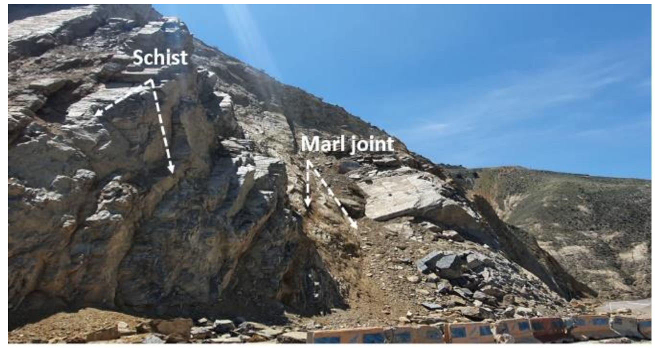

Fig. 6 Slopes dominated by schist and marly schist

In the majority of the studied areas along the road, the rock debris is mainly composed of stratified fractured schists, sometimes enriched with marly fillings. The slope geometry reveals relatively steep banks, which pose significant regional stability issues.

Indeed, due to their stratification and flaky structure (Figure 7), the schists exhibit a natural tendency to fracture along their bedding planes, which can weaken the overall strength of the mass. This inherent fragility increases the risk of landslides and collapses, particularly in areas where rock benches are exposed to mechanical stress or extreme weather conditions.

Fig. 7 Flaky structure of schists affected by an intense fracturing network

Furthermore, the marly-filled joints, which act as points of weakness in the rock mass, further complicate the situation, especially during bad weather when these joints tend to become saturated with water, leading to a significant reduction in cohesion among rock particles (Figure 8).

This water saturation can also cause additional pore pressure, decreasing the stability threshold of the slope and thereby increasing the risks of instability.

Fig. 8 Affected schist mass showing several marly joints

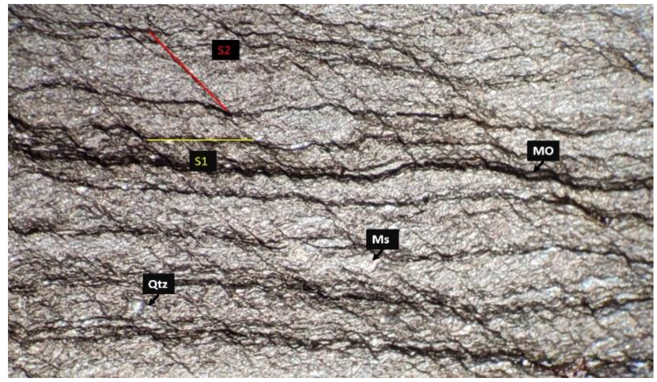

Fig. 9 Photographs of thin sections: S2 foliation with white micas (muscovite), quartz (qtz), and opaque minerals (observed in polarizing light microscopy)

From a petrographic point of view, we conducted a series of schist sample collections for examination under a micro-probe (Figure 9).

The results obtained show that the S1 foliation, marked by white mica, quartz, and opaque oxides, is folded and transposed, along with a second foliation S2.

The following tables comprehensively summarise the geological and tectonic surveys, highlighting key findings, observations, and measurements obtained from the various sections studied (Tables 1, 2 and 3).

Table 1. Summary tables of geological and tectonic surveys (station 1-9)

N Station		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
N Section		**1**	**1**	**2**	**2**	**2**	**3**	**4**	**4**	**7**
Road	Direction	N180	N185	N190	N190	N185	145	N150	N160	N335
	Dip	6	4	4	4-5	8-9	6-7	8	8	7-8
Slope	Dip Direction	N90	N120	N100	N100	N90	N245	225	250	250
	Dip	35 SE	35 SE	35	35-40	20-30	15-45	25-30 NW	15	40 NW
	High	20	24	26	27	28	35	33	37	38
Stratification	Dr	80-90	120	N100	100	90	240		250	250
	Dip	35 SE	30 SE	35 SE	35-40 SE	20-30 SE	35		15 NW	40 NW
	Lithology	Schist	Schist	Schist	Quartzite	Quartzite	Schist	Schist	Schist	Marly schist
Discontinuity	Type	Fracture	Fracture	Joint	Fracture	Fracture	Fracture	Fracture	Fracture	Fracture
	Direction	330-335	330	260	255	255	265	270	280	90
	Dip	50-60 SW	50-60 S-W	40-80	45 NW	45-55 NE	50-60 SW	45 NW	50 SE	85 NW
	Thickness	0.10	3	0.40	0.1	0.4	0.30	0.10	0.2	0.1

Table 2. Summary tables of geological and tectonic surveys (station 10-17)

N Station		**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**
N Section		**7**	**8**	**9**	**9**			10	10
Road	Direction		N40	N335			N100	N350	N350
	Dip		8 SW	6 SW			6 S	6 S	6 S
Slope	Dip Direction	245	170	230	N220	N220	240	265	260
	Dip	45 NW	35	45 NW	45 NW	45 NW	40-45	35-40	40
	High	38	17	25	27	28	40	40	40

N Station		10	11	12	13	14	15	16	17
Stratification	Dip Direction		220	230	220	220	240	260	260
	Dip		40	35 NE	45 NE	45 NE	40	35-40	40
	Lithology		Schist	Schist	Schist	Schist	Schist	Schist	Schist
Discontinuity	Type	Fracture	Fault	Joint	Joint	Joint	Fault	Fault	Fracture
	Direction	N90	N270	N150	N160	N130	N280	N270	N140
	Dip	80 NW	45 NW		65SW	70-75	35-45 NW	45-50 NW	85 SW
	Thickness				0.05				0.02
Schistosity	Dip Direction				N220	N225			N250
	Dip				50 NE	45 NE			Slate Shale
	Lithology	Schist	Schist	Schist	Schist	Schist	Schist	Schist	Schist

Table 3. Summary tables of geological and tectonic surveys (station 18-25)

N Station		18	19	20	21	22	23	24	25
N Section		10	10	10	11	11	11	11	11
Road	Direction	N350	N355	N140	N140	N150	N 140	N150	N 160
	Dip	6 S	6 N	6 N	6 NW	7	8 NW	8	7
Slope	Dip Direction	265	260		230	220	N 190	225	
	Dip	45	30		65	65-75	60-70	60	
	High	35	35		15	25	30	28	27
Stratification	Dr	265	260	250	230	220	190	225	250
	Dip	45 N	30	40	65-75	75 E	60-70	60	40-45
	Lithology	Schist	Schist	Schist	Sandy Schist	schist	Marly Schist	Marly Schist	schist
Discontinuity	Type	Fracture	Marly Join	Marly Join	Marly Join	fracture	fracture	Marly Join	Marly Join
	Direction	125	140	170	220	240	190	240	250
	Dip	80 NE	45 W	55 W	70	60-70	60-70	30-40	45
	Thickness		0,8	0,7	0,5	1	0,5	0,6	0,4
Schistosity	Dip Direction	N 165	N 160	N 165	N220	N220	N220	N250	N245
	Dip	10	5	15	70 NE	45	30-40	30-40 N	40 N
	Lithology	Marly Schist	Marly Schist	Marly Schist.	Marly Schist	Marly Schist	Marly Schist.	Clay	Clay

2.4. Sections 1 to 5

The treatment zone of these sections spans 503 meters, with slope heights ranging from 15 to 35 meters.

- The main bench directions of the slopes in sections 1 and 2 are N90-N120.
- The main bench directions of the slopes in sections 3 and 4 are N245.
- Matrix: It consists of a schistose and shaly schist matrix interspersed with marl joints and sandstone benches.
- Dip: Sections 1, 2, 3, 4, and 5 are characterized by layers dipping at angles between 30° and 65°.

- Direction: Sections 1, 2, 3, 4, and 5 are characterized by layers oriented towards N0-N130 and N220.
- Tectonics: Section 1 exhibits a fracture in the N330 direction, section 2 displays a marl joint in the N260 direction, section 3 shows folding, and section 4 exhibits a fracture in the N280 direction.

2.5. Sections 6 to 9

These sections have a length of 260 meters, with a rocky slope reaching a height of 25 to 35 meters. The slope is oriented towards N240. The most abundant facies consist of shales and marl-shales.

- Dip: Sections 6, 7, 8, and 9 are characterized by layers dipping at angles between 38° and 80°.
- Direction: Sections 6, 7, 8, and 9 are characterized by layers oriented between N40 and N160.
- Tectonics: Structural surveys conducted in section S7 revealed the presence of two fracture families: F1 with a direction of N90 and a dip of 80° towards the northwest, and F2 with a direction of N150 and a dip of 65°. Section S9 is affected by a fold and a joint with a direction of N130-N160.

2.6. Sections 10 and 11

These two sections have a length of 375 meters, with a rocky slope reaching a height of 40 meters. The slope is oriented towards N240-N220. The stratigraphic sequence of these sections consists of fractured shales, mica-schists, and loose marly clays.

- Dip: Sections 10 and 11 are characterized by layers with dips ranging from 30° to 60°.
- Direction: Sections 10 and 11 are characterized by layers with directions ranging from N260 to N230.
- Tectonics: The two sections are separated by an anticlinal fold in a chaâba. Section 10 is marked by the presence of two faults and a fracture with a direction of N140. Section 11 is affected by two major fractures and four joints, approximately oriented towards N240. Some detached blocks are observed at the foot of the slope.

2.7. Sections 13 and 14

These two sections have a length of 390 meters, with a rocky slope reaching a height of 40 meters. In these two sections, the foliated shales are affected by marl joints and a family of fractures, contributing to the slope's sliding.

- Dip: Sections 13 and 14 are characterized by layers with dips ranging from 45° to 75°.
- Direction: Sections 13 and 14 are characterized by layers with directions between N90 and N180.
- Tectonics: Section 13 is characterized by the presence of an anticlinal fold at point 6. This section is marked by two loose meter-sized joints filled with clay, oriented towards N160. These joints run parallel to the road axis, facilitating the movement of rocks towards it. Both sections exhibit sub-parallel fractures with directions ranging from N120 to N140.

2.8. Sections 17 and 18

The treatment zone of these two sections spans 190 meters, with slope heights ranging from 30 to 35 meters. The main bench direction of the slope is N95. The matrix consists of shales, mica schists, and marl joints.

- Dip: Sections 17 and 18 are characterized by layers with dips ranging from 35° to 80°.
- Direction: Sections 17 and 18 are characterized by layers with directions ranging from N60 to N90.
- Tectonics: It is marked by an anticlinal fold (section 18) surrounded by two faults oriented towards N245. Section 17, with disturbed stratification, is affected by fractures, marl joints, and schistosity in various directions. The mentioned tectonic structure has facilitated the sliding and collapse of unstable masses.

2.9. Sections from 19 to 21

The treatment zone of the three sections, 19, 20, and 21, extends for approximately 200 meters, with slope heights ranging from 10 to 20 meters.

- The main bench direction of the slope is N300. The matrix consists of shales, shaly shales, and marls.
- Dip: Sections 19, 20, and 21 are characterized by layers dipping between 25° and 70°.
- Direction: Sections 19, 20, and 21 are characterized by layers with directions ranging from N110 to N290.
- Tectonics: Section 19 is marked by a recumbent fold and a wet marl joint with a direction of N250. Section 19 and section 20 are connected at a synclinal fold. The fractures in section 21 are oriented towards N170. Some calcitic joints appear in section 20.

3. Results and Discussion

3.1. Qualitative Geohazard Assessment

The geological section established across several road segments illustrates a relatively complex sedimentary sequence composed of alternating shales and marl shales, with intercalations of sandstones.

An overall synthesis of the geological and structural context of the area is summarized as follows (Figure 10):

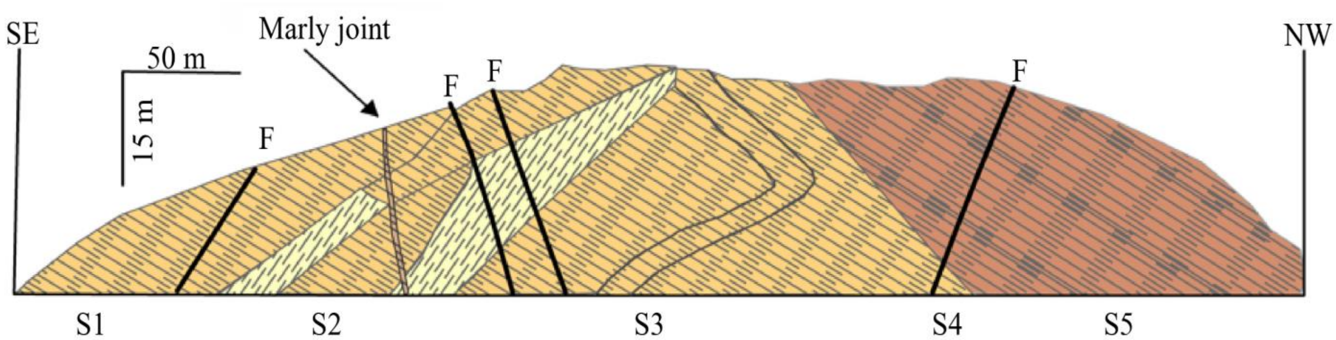

Fig. 10 Geological section from S1 to S5

- The shales constitute the majority of the layers, especially in S1, S2, and part of S3. They appear to be relatively homogeneous in the visible part of the section.
- Marl shales are present alternating with shales, mainly in sections S3, S4, and S5.
- The proportion of marl shales seems to increase towards the northwest.
- Sandstones: Sandstones appear as thin intercalations within the shales and marl shales, primarily in section S2 and at the beginning of S3.

Several fractures and faults traverse the different layers. These fractures are sub-vertical and affect all lithological units present (shales, marl shales, and sandstones). They are more concentrated in sections S2 and S4, potentially indicating areas of greater fragility. The presence of "marl joints" represents potential weakness planes within the rock mass (Figure 11).

Fig. 11 Weak plane in the form of a marly joint

The geological and tectonic study of the unstable sections reveals the heterogeneity of the formations encountered, notably the presence of multiple structural families (folded, faulted, and fractured shales with marl-filled joints) affecting the stability of the slopes. The instability observed in the studied sections corresponds to relatively slow movement on unfavourable dips, downward and outward from the massif. The risks identified in this area are of different nature:

Sliding and collapse of unstable terrains:

This type of risk has been observed in sections S2, S5, S8, S10, S11, S12, S14, S17, S18, and S21. The dip angle of the discontinuities is crucial. In stations 1 and 5, discontinuity dips of 70° and 80° are observed, respectively. Given that these discontinuities are oriented parallel or sub-parallel to the slope, they represent potential sliding planes (Figure 12). This explains the landslides occurring in this section, where shear stresses visibly exceed shear resistance along these planes. Additionally, the thin thickness of the layers (0.05m and 0.1m) in these stations exacerbates the risk. This risk is caused by the presence of swelling marl joints in a context of marly shale alternations, parallel fracturing along loose joints, the presence of rock blocks parallel to the road, topographic depressions (sections 11 and 18), and water infiltration into joints and fractures (section 18).

3.2. Rockfall

This type of risk has been observed in sections S1, S2, S17, and S20. Heavily inclined discontinuities (70° and 80°) are the main cause of the observed rockfalls, especially in highly weathered areas. Thus, the presence of fractures and joints in a sloped context increases this risk. It results from the presence of breccias and synsedimentary faults. Hard and fractured layers have been located above loose layers in areas with steep topography and the absence of vegetation.

Fig. 12 Several detached blocks are observed in section 11

Geotechnical jointed rock behavior refers to the response of rock masses containing natural or induced fractures (joints) to external forces and environmental conditions. These joints significantly influence the mechanical properties and stability of the rock mass. Key aspects of geotechnical jointed rock behavior include:

- Anisotropy: Jointed rock exhibits mechanical properties that vary with direction due to the presence of joints, affecting parameters such as strength, stiffness, and permeability.
- Strength: The overall strength of jointed rock is influenced by the properties of the intact rock and the joints. Factors such as the orientation, spacing, roughness, and persistence of the joints affect failure mechanisms.
- Deformation: Under stress, joints can deform by dilation, closure, or sliding, impacting the overall deformability and stability of the rock mass.
- Stability Analysis: Geotechnical engineers analyze jointed rock masses to assess their stability under conditions such as excavation, slope stability, tunneling, and foundation design. Understanding joint behavior is crucial for accurate assessments and risk management.
- Fluid Flow: Joints provide pathways for fluid movement within the rock mass. Analyzing fluid flow behavior in jointed rock is essential for groundwater management, seepage analysis, and designing underground structures.
- Rockfall Hazard: The presence of joints increases the risk of rockfall events, posing hazards to infrastructure, transportation networks, and human safety. Effective risk assessment and mitigation involve understanding joint orientations, discontinuity spacing, and potential failure mechanisms.

3.3. Qualitative Geohazard Assessment

The Jointed Rock model is an anisotropic, elastic, perfectly plastic material model designed to depict a continuum model for jointed rock formations [13].

This model integrates and models, in addition to the intrinsic characteristics of intact rock, the rock discontinuities, thus enabling it to adopt geomechanical characteristics that condition the stability of the entire massif. It also allows for the simulation of the direction and dip of the stratification, making it a model that reflects the overall behavior of the massif.

In the jointed rock, the discontinuity planes control the strength, deformational and hydraulic properties, and general behavior of rock masses [14]. Discontinuity" refers to any plane of separation or weakness within a rock mass and likely originates from or tectonic (joints and faults) processes.

In road excavation projects, the relative orientation of discontinuities can affect the stability of the excavation slopes. The relative orientation of discontinuities may determine whether the excavation wall is stable or not (Figure 13) [15].

Fig. 13 Unfavorable orientation of discontinuities

The Jointed Rock model incorporates the following parameters [16].

- Elastic parameters of the intact rock, including Young's modulus E1 and Poisson's ratio V1 (Figure 14).
- Anisotropy resulting from stratification is characterized by parameters E2 and V2, which define the stiffness of the mass perpendicular to the direction of stratification.
- The shear stiffness in the direction of anisotropy is represented by the shear modulus G2.
- Shear failure according to Coulomb: cohesion, friction angle and dilatancy
- Definition of joint directions: number of joint directions, dip angle and strike.

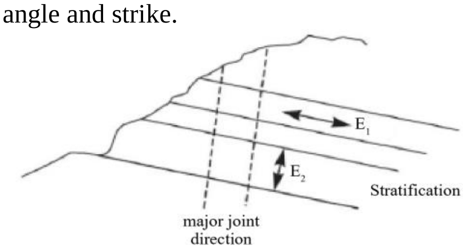

Fig. 14 Jointed rock model [16]

Figure 15 below presents an example of the calculation results of deformation using the joint rock modulus.

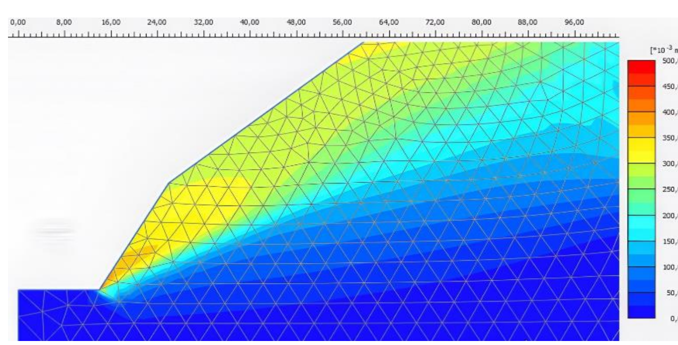

Fig. 15 Illustration of jointed rock results

3.4. Results

Based on the developed geotechnical models, several series of analyses regarding the stability of rocky slopes have been conducted. These analyses consider various configurations, including stratification patterns and the orientation of fracture networks (Figure 16).

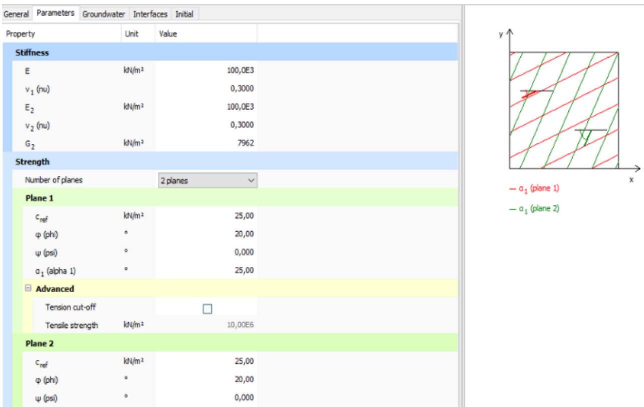

Fig. 16 Calculation model selected based on two planes, section 10

For example, in section 10, the calculations performed following two planes of schistosity indicate that the unstable zone is located at the foot of the slope and is limited in depth.

Once this zone is precisely delineated, it could be effectively stabilized through a simple surface treatment, thereby ensuring the safety and performance of the slope without major complications (Figure 17).

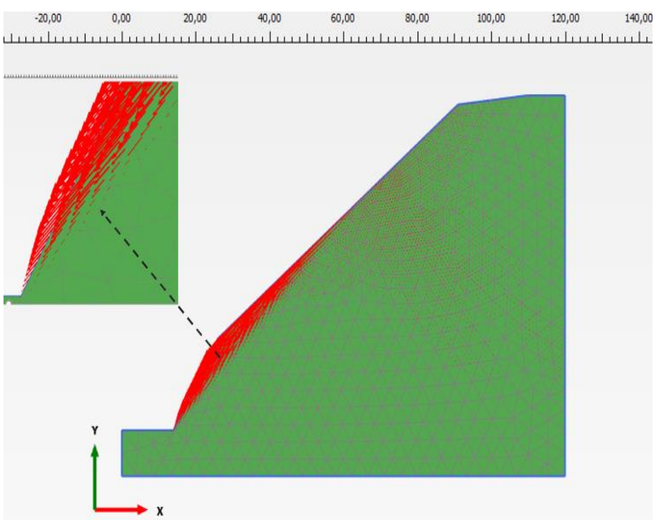

Fig. 17 Calculation results for section 10, according to two schistosity planes

In contrast, the situation becomes more complex in sections where the presence of multiple fracture planes characterizes schistosity. Several signs of instability are observed throughout the slope, affecting nearly its entire height.

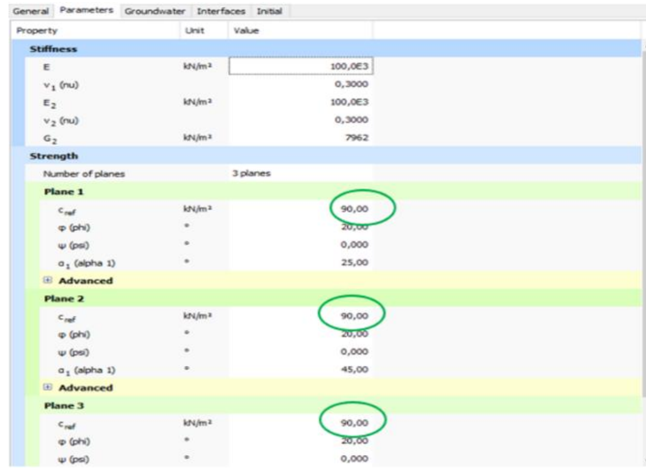

Fig. 18 Calculation model selected according to multiple planes, section N° 10

In this context, the overall stability of the slope is strongly influenced by dihedrals, which manifest as joints resulting from an unfavorable angular arrangement of the rock layers. These dihedrals promote the emergence of potentially critical sliding surfaces (Figure 19).

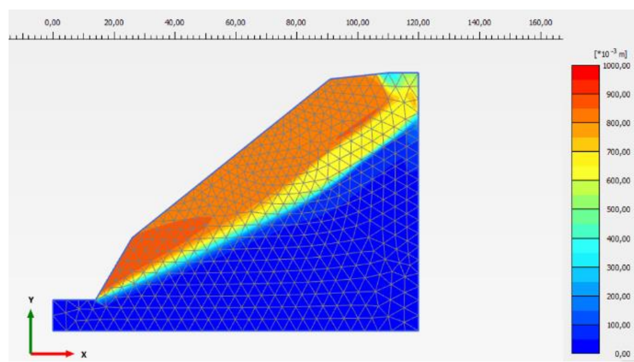

Fig. 19 Model with three planes of schistosity

Such a geological configuration necessitates the implementation of reinforcement solutions, such as the installation of anchors. These anchors would help stabilize the slope by increasing the overall cohesion of the construction materials, thereby reducing the risk of failure.

4. Conclusion

In conclusion, this study highlighted the geotechnical complexity of fractured rock masses along the Taza-Al Hoceima highway through an integrated approach that combines thorough field investigations and advanced numerical modeling. The geological analysis revealed significant lithological complexity, with intercalations of schists, marly schists, and sandstones, as well as pronounced fracturing that affects the stability of the structure. Detailed structural surveys enabled the characterization of the orientations and inclinations of the layers and discontinuities, illuminating several potential weakness zones. The in-situ analysis confirmed the presence of risk areas, increasing the likelihood of landslides and rockfalls. "Using the Joint Rock module has demonstrated the importance of simulating the complex interaction between intact rock and the identified discontinuities. The model's ability to integrate the nonlinear behavior of materials and the anisotropic properties of fractured masses has resulted in more realistic outcomes than those obtained from traditional approaches. This modeling has allowed for the visualization of stress distributions and the delineation of critical areas of potential weakness and the risks of collapse or sliding. However, it is essential to recognize certain limitations of numerical modeling. Although these tools are powerful, they rely on assumptions and parameters that must be carefully validated in the field. Observations on-site, combined with the expertise of professionals, are crucial to complementing and refining the conclusions obtained from modeling. These observations allow for considering factors and variabilities that may not be fully captured by numerical models. These results also underscore the importance of continuing geotechnical investigations, particularly concerning the impact of water and material alterations on the long-term evolution of rock mass behavior. Furthermore, the adopted multidisciplinary approach is strongly recommended for engineering projects in similar complex geotechnical contexts. In the future, it is envisioned that various loading scenarios and environmental conditions will be explored and simulated, with particular attention given to the appropriate selection of variables that condition the stability of roadway slopes. The objective is to develop a robust model that facilitates the application of artificial intelligence methods, particularly neural networks, which allow for the optimization of the simulation and prediction process.

References

[1] H.H. Einstein et al., "The Effect of Discontinuity Persistence on Rock Slope Stability," *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, vol. 20, no. 5, pp. 227-236, 1983. [CrossRef] [Google Scholar] [Publisher Link]

[2] Ghader Saadati et al., "AI-Powered Geotechnics: Enhancing Rock Mass Classification for Safer Engineering Practices," *Rock Mechanics and Rock Engineering*, pp. 1-31, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[3] Mohamed Master, "*Susceptibility to Ground Movements in the Province of Chefchaouen (Central Rif, Morocco)*," Thesis, Earth Sciences, University of Western Brittany - Brest, pp. 1-321, 2011. [Google Scholar] [Publisher Link]

[4] H. Harmouzi et al., "Geomorphological and Geological Analysis of Akchour Landslide (Rif, Morocco)," *Geo-Eco-Trop*, vol. 42, no. 1, pp. 19-32, 2018. [Google Scholar] [Publisher Link]

[5] R.E. Hammah, T. Yacoub, and J.H. Curran, "Variation of Failure Mechanisms of Slopes in Jointed Rock Masses with Changing Scale," *Third Canada-US Rock Mechanics Symposium*, Toronto, Canada, vol. 3956, pp. 1-8, 2009. [Google Scholar] [Publisher Link]

[6] J. Rousseau, "*Numerical Modeling of the Dynamic Behavior of Structures under Impact with a Discrete Elements / Finite Elements Coupling*," Thesis, Joseph Fourier University, pp. 1-200, 2009. [Google Scholar] [Publisher Link]

[7] ASTM-D6032/D6032M–17, Standard Test Method for Determining Rock Quality Designation (RQD) of Rock Core, ASTM International. [Online]. Available: https://webstore.ansi.org/standards/astm/astmd6032d6032m17#:~:text=1.1%20This%20test%20method%20covers,such%20as%20mining%20and%20civil

[8] Z.T. Bieniawski, *Engineering Rock Mass Classifications: A Complete Manual for Engineers and Geologists in Mining, Civil, and Petroleum Engineering*, John Wiley & Sons, pp. 1-272, 1989. [Google Scholar] [Publisher Link]

[9] Evert Hoek, Practical Rock Engineering, RocScience, 2007. [Online]. Available: https://www.rocscience.com/assets/resources/learning/hoek/Practical-Rock-Engineering-Full-Text.pdf

[10] E. Hoek, and E.T. Brown, "Practical Estimates of Rock Mass Strength," *International Journal of Rock Mechanics and Mining Sciences*, vol. 34, no. 8, pp. 1165-I186, 1997. [CrossRef] [Google Scholar] [Publisher Link]

[11] Noemie Lebret, "*Structural and Metallogenic Context of the Magnetite Skarns of Beni Bou Ifrour (eastern Rif, Morocco) Contributions to the Geodynamic Evolution of the Western Mediterranean*," Thesis, University of Orléans, pp. 1-476, 2014. [Google Scholar] [Publisher Link]

[12] G. Suter, "Geological Maps of the Rif at 1/500,000, Sheets 245a and 245b," *Notes and Memoirs of the Geological Service of Morocco*, 1980. [Google Scholar]

[13] Magdalena Stelzer, "*Numerical Studies on the PLAXIS Jointed Rock Model*," Mather Thesis, Graz University of Technology, 2015. [Google Scholar]

[14] Hatef Hashemi et al., "Evaluation of Rock Nail Wall Performance in Jointed Rock Using Numerical Method," *Geotechnical and Geological Engineering*, vol. 33, pp. 593-607, 2015. [CrossRef] [Google Scholar] [Publisher Link]

[15] Luis Gonzalez de Vallejo, and Mercedes Ferrer, *Geological Engineering*, CRC Press, pp. 1-700, 2011. [Google Scholar] [Publisher Link]

[16] R.B.J. Brinkgreve, W. Broere, and D. Waterman, "*Plaxis: 2D - Version 8*," Delft University of Tehnology & PLAXIS bv, pp. 1-18, 2004. [Google Scholar] [Publisher Link]