EEET ECOLOGICAL ENGINEERING & ENVIRONMENTAL TECHNOLOGY

Ecological Engineering & Environmental Technology, 2025, 26(10), 86–102
https://doi.org/10.12912/27197050/209857
ISSN 2719–7050, License CC-BY 4.0

Received: 2025.08.19
Accepted: 2025.09.15
Published: 2025.10.01

Geohazard assessment and ground movement mapping for cliff stabilization along RN16 in Chefchaouen, Morocco

Adnane Medrari[1], Mohamed Mastere[1,2], Brahim Benzougagh[1,3]

[1] Geophysics and Natural Hazards Laboratory, Department of Geomorphology and Geomatics, Scientific Institute, Mohammed-V, University in Rabat, Avenue Ibn Battouta, Agdal, P.B 703, 10106 Rabat, Morocco
[2] School of Public Management, Governance and Public Policy, College of Business & Economics, University of Johannesburg, South Africa
[3] Laboratory of Geoengineering and Environment, Cartography and Tectonophysics team (CaTec), Department of Geology, Faculty of Sciences, Moulay Ismail University, Meknes, Morocco
* Corresponding author's e-mail: brahim.benzougagh@is.um5.ac.ma

ABSTRACT

This study aims to advance the scientific understanding of rockfall and landslide hazards in tectonically active mountainous regions by developing a generalizable framework for assessing and mitigating slope instability, using a high-risk segment of the RN16 road at PK156+000 in Chefchaouen, Morocco, as a case study. The research seeks to characterize instability mechanisms and evaluate stabilization strategies to enhance infrastructure safety. The study integrates field-based geological and structural assessments with geotechnical modeling. Fracture mapping and instability diagnostics were conducted across a 2.5-km cliff segment, identifying 29 unstable sites. Geotechnical analyses utilized PHASE 2 and RocFall software to model slope stability and rockfall trajectories. Four stabilization variants – tunnels, false tunnels, rockfall nets with anchors, and slope reprofiling – were evaluated through stability calculations and cost-benefit analyses. The analysis identified Section 2 as having a high hazard level (risk degree II, frequent instability) due to its 70–80° slopes and conjugate fractures. Stability calculations showed safety factors > 1.5 (no seismic activity) and > 1.1 (with seismic activity). A hybrid approach combining rockfall nets and slope reprofiling was found to be the most cost-effective, reducing rockfall risks by intercepting blocks and stabilizing slopes. The study is limited by its focus on a single site, which may restrict direct applicability to other geological settings. Long-term effectiveness depends on maintenance and monitoring, which were not fully assessed due to time constraints. The proposed framework provides engineers and policymakers with a scalable methodology for mitigating geohazards, enhancing road safety, and ensuring infrastructure resilience in mountainous regions. This research offers a novel integration of field diagnostics, numerical modeling, and cost evaluations, contributing a robust model for rockfall mitigation. Its findings are significant for geohazard management in tectonically active regions, offering insights applicable to similar global settings.

Keywords: geohazard assessment, cliff stabilization, rockfall protection, geotechnical engineering, RN16, Chefchaouen, Morocco.

INTRODUCTION

Rockfall and landslide hazards in mountainous regions pose significant risks to infrastructure, transportation networks, and human safety, particularly in tectonically active areas with complex geological settings (Mahmood et al., 2024; Eze et al., 2025). These geohazards are driven by a combination of steep topography, fractured rock masses, and external triggers such as seismic activity and heavy rainfall (Hadji et al., 2017; Dahmani et al., 2024). In regions like the Rif in northern Morocco, characterized by Alpine orogeny, schistose bedrock, and Mediterranean climate with seasonal rainfall (300–800 mm annually), the potential for rockfall events is exacerbated

(Chalouan and Michard, 2004; El Brahimi et al., 2024). The RN16 road in Chefchaouen Province, Morocco, exemplifies these challenges, with a 2.5-km cliff segment at PK156+000 exhibiting frequent rockfalls and landslides that threaten a critical transportation artery (Benzougagh et al., 2022; Taj et al., 2024).

Significant progress has been made in understanding rockfall mechanisms and developing mitigation strategies. Field-based fracture mapping and geotechnical modeling, such as PHASE 2 and RocFall, have improved the characterization of slope instability (Assefa et al., 2017; Mastere et al., 2020). Stabilization techniques, including rockfall nets, gabion walls, slope reprofiling, and tunnels, have been successfully implemented in various geological contexts (Hencher, 2010; Loew et al., 2010). For instance, Li et al. (2024) demonstrated the efficacy of rockfall nets in high-steep slopes, while Popescu and Zoghi (2006) highlighted the cost-effectiveness of slope reprofiling in certain settings. Recent advancements also include real-time monitoring systems to enhance early warning capabilities (Huang et al., 2025). However, challenges persist, particularly in integrating field diagnostics with numerical modeling to develop cost-effective, site-specific solutions for tectonically active regions (Capobianco et al., 2025). Existing studies often focus on isolated aspects of rockfall mitigation, such as modeling or structural interventions, but rarely combine these with comprehensive cost-benefit analyses or applicability to complex lithologies like schistose bedrock (Maheshwari et al., 2023).

Despite these advancements, several knowledge gaps remain. First, there is a lack of integrated frameworks that combine geological assessments, geotechnical modeling, and economic evaluations to address rockfall hazards in heterogeneous, tectonically active settings. Second, few studies provide scalable methodologies that can be adapted to other mountainous regions with similar geological complexities. Third, the interplay of preparatory factors (e.g., fracture networks, lithology) and triggering factors (e.g., rainfall, seismicity) is underexplored in the context of site-specific stabilization strategies. This study seeks to fill these gaps by developing a comprehensive, scientifically grounded framework for assessing and mitigating rockfall hazards along the RN16 road at PK156+000 in Chefchaouen, Morocco.

This research aims to advance the scientific understanding of rockfall and landslide mechanisms in tectonically active mountainous regions by characterizing instability drivers, evaluating stabilization strategies, and proposing a scalable mitigation framework. Specifically, the study seeks to: (i) elucidate the geological and structural controls on slope instability in schistose bedrock settings; (ii) quantify the effectiveness of multiple stabilization strategies (tunnels, false tunnels, rockfall nets, slope reprofiling) through geotechnical modeling and cost-benefit analyses; (iii) develop a generalizable methodology for geohazard mitigation applicable to similar global settings.

We hypothesize that the integration of field-based fracture mapping, advanced geotechnical modeling (PHASE 2 and RocFall), and cost evaluations will identify a hybrid stabilization approach (e.g., combining rockfall nets and slope reprofiling) as the most effective and cost-efficient solution for the RN16 site. We expect that conjugate fracture systems and water infiltration are the primary drivers of instability, with steep slopes (70–80°) amplifying risks. The study anticipates that the proposed framework will offer a robust model for mitigating geohazards in tectonically active regions, balancing safety, cost, and environmental impact.

By addressing these gaps, this study contributes novel insights into the interplay of geological and environmental factors in rockfall initiation and provides a practical, evidence-based approach to infrastructure protection. The findings are expected to inform engineers and policymakers in designing resilient transportation networks in geohazard-prone areas worldwide.

MATERIALS AND METHODS

Study area

The study area is situated along the RN16, a major road connecting Tangier and Saidia. The specific section of interest is located 12 km southeast of Oued Laou and approximately 35 km northeast of Chefchaouen. The road descends through a series of switchbacks into the Targha valley. The study area is bound by coordinates X = 535472.11 / Y = 532219.381 in the south, near Targha, and X = 536670.859 / Y = 530164.851 in the Azenti area (Figure 1).

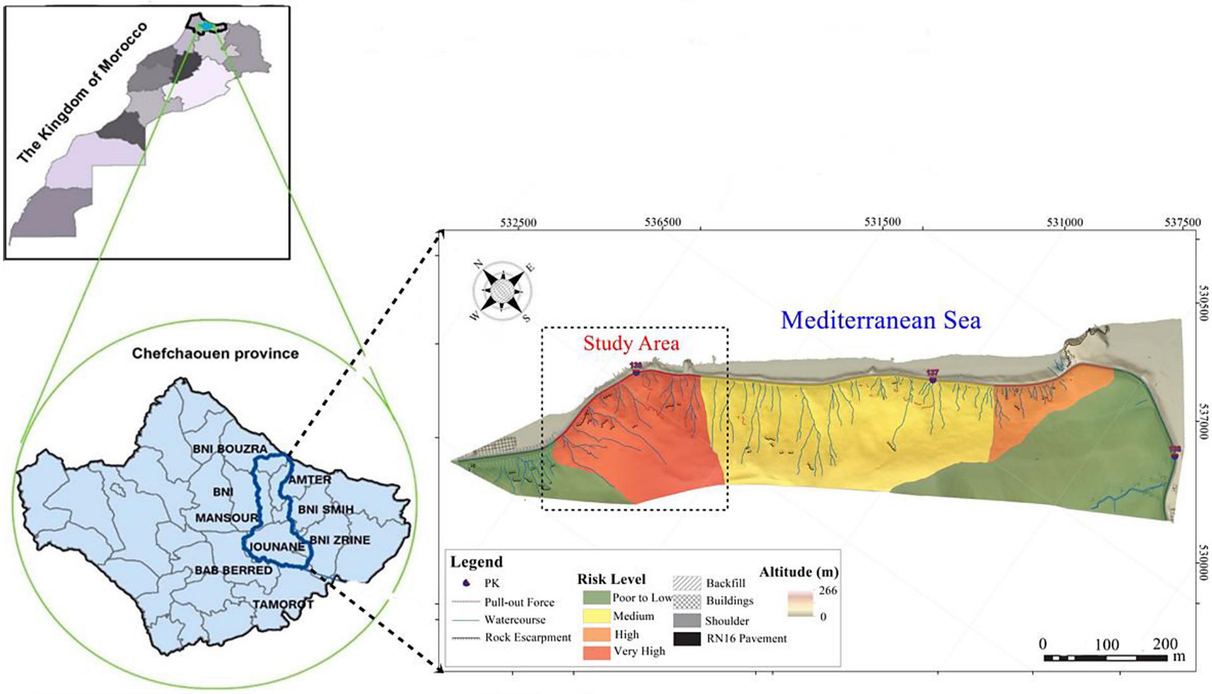


Figure 1. Location map of the study area

SITE DESCRIPTION AND GEOLOGICAL SETTING

The cliff extends for 2.5 km in a northwest direction, with a width ranging from 0.5 to 1 km. Altitudes vary from 10 m to 266 m above sea level. The terrain is highly rugged, dissected by a dense network of gullies originating from the crests and rocky escarpments. The slope morphology presents a stepped appearance, with steep to very steep slopes transitioning to gentler inclines near the cliff top (Figure 2). The majority of the slopes face northeast and east (68%), while north and northwest-facing slopes are concentrated in the northwest part of the cliff (12%). Southeast, south, and southwest-facing slopes are less common (20%). Slope angles vary considerably: 26% are less than 20 degrees (near the coast and crests), 57% range from 20 to 40 degrees, and 16% exceed 40 degrees, characterizing rocky escarpments and cliffs.

The geology of the area is characterized by the lower Sebtides, with outcrops of micaschists belonging to the Filali unit. These micaschists are exposed in rocky escarpments and road cuts. The northeast-facing slopes are generally covered by polygenic deposits consisting of clays and schist fragments ranging in size from centimeters to

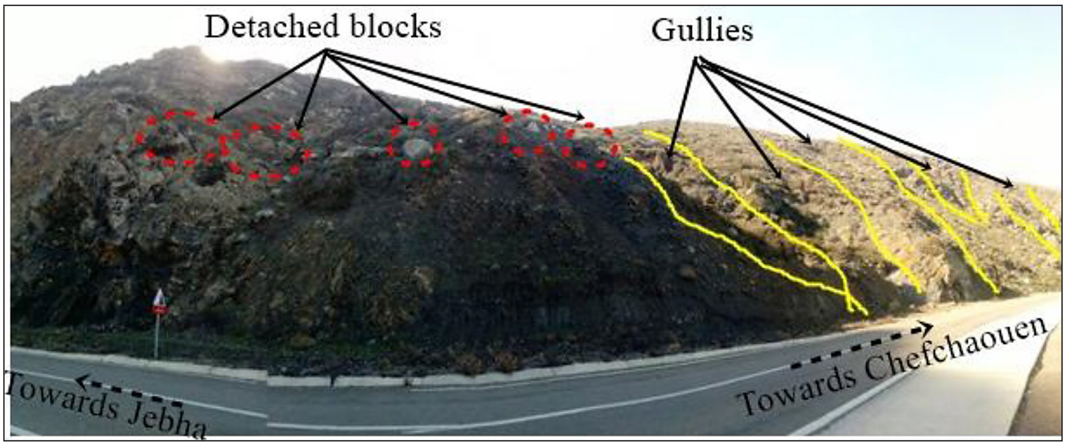


Figure 2. Geological features of the study area – detached blocks and erosion gullies

meters. The crests are capped by loess-gravelly cover deposits, often masked by surface vegetation. Colluvial deposits, scree, and chaotic debris deposits with variable thicknesses (up to 10 meters) are found along the road trace. These deposits consist of uncemented, angular micaschists fragments of varying sizes, extending from the base of the cliffs (Figure 3 and 4).

INSTABILITY DIAGNOSIS AND RISK MAPPING

There are a number of classifications of instabilities, using different criteria. A classification is defined to reduce a multitude of phenomena—different but related—into a few easily recognizable and usable groups based on common attributes

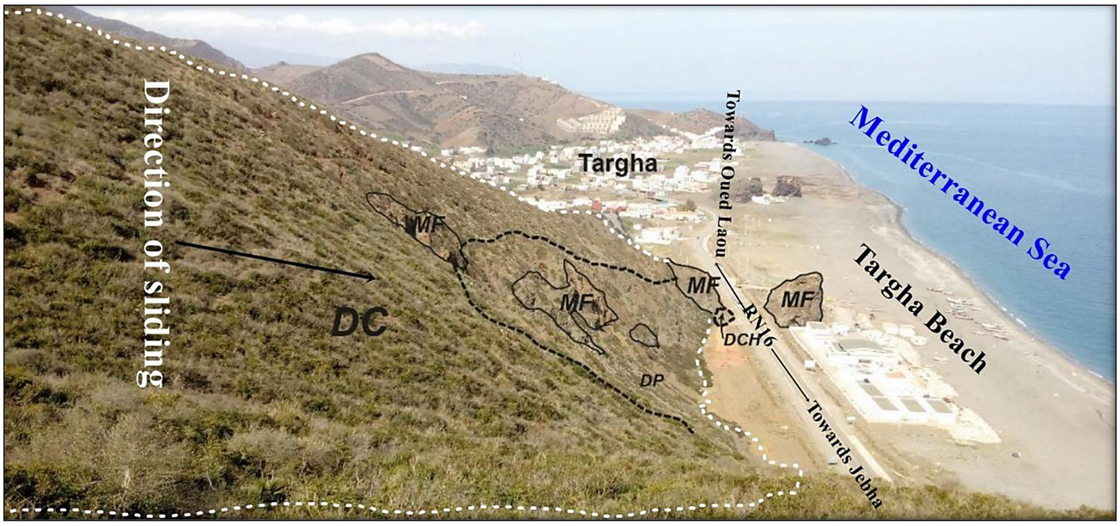


Figure 3. Panoramic view of the northwest slope of the cliff showing the different lithological units in the study area: (MF) – mica schists from the Filali unit, (DCH) – chaotic deposits, (DP) – polygene deposits, (DC) – colluvial deposits

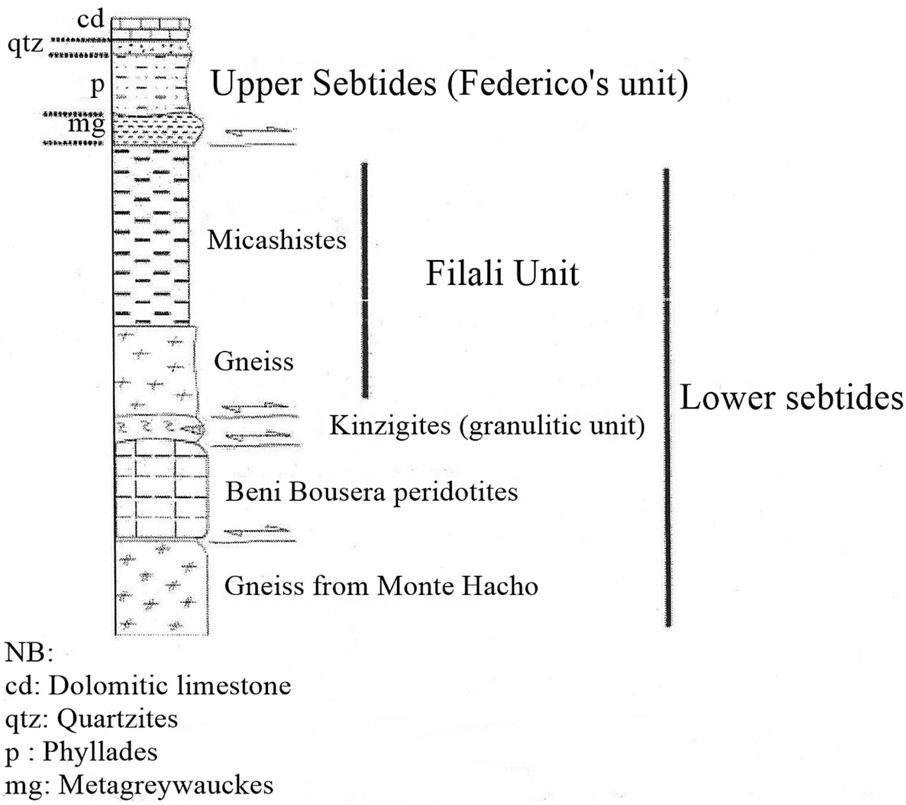


Figure 4. Synthesis lithostratigraphic column schematically representing the study area

(Hunger, 2005; Catani et al., 2025). It is also a means of rationally seeking appropriate remedies and helping to decide on the need for reinforcement, then choosing overall between reinforcement systems. Most recent classifications remain based on two factors, the type of movement and the type of materials, to which are added the type and quantity of fluid involved in the movement, i.e., air and, above all, water (Wei et al., 2023; Leyssens et al., 2025). Five main types of phenomena, causing significant displacement of material on embankments and slopes, can be distinguished: (i) rockfalls, falling rocks, and landslides, (ii) mowing, (iii) slips, (iv) lateral movements, and (v) flows. During the field missions and the visual examination of the cliff, particular attention was given to these phenomena. However, only the first and third phenomena appear to be predominant, with landslides affecting the cover soils.

The diagnostic phase of the study identified 29 sites exhibiting instability. The observed ground movements were classified as: (i) landslides (8 sites); (ii) rockfalls (6 sites); (iii) stone or block falls (5 sites); (iv) Gullies associated with debris flows (10 sites) (Figure 5). The cliff was divided into five sections for detailed analysis. Sections 1 and 5 were deemed relatively stable. The primary concerns were focused on sections 2, 3 and 4. Section 2, purpose of this study – characterized by quasi-vertical slopes reaching 100 m in height, with schists at the base, polygenic deposits in the middle, and cover soils at the top. This section exhibited a high frequency of rockfalls, block falls, and debris flows. Section 3 – the bedrock is largely covered by soil, with some rocky escarpments. Instability is manifested as superficial landslides, rockfalls and locally deep erosion. Displaced metric blocks pose a significant hazard to the road. Section 4 – features a quasi-vertical cliff reaching 80 m in height. A landslide affects the cover soils, and small, precariously balanced blocks are present on the slope.

Section 2 – this section, which is 578 m long and extends in a WNW-ESE direction, takes the form of a nearly vertical slope, reaching a height of 100 m, carved out of the lower part of the schistose bedrock, topped in its middle section by polygenic deposits resulting from the weathering of mica schists, while the summit is almost entirely covered by overburden, where the bedrock is almost completely absent. The mentioned section is characterized by a significant frequency of varied and violent instabilities, including landslides, rock falls, and very narrow and deep

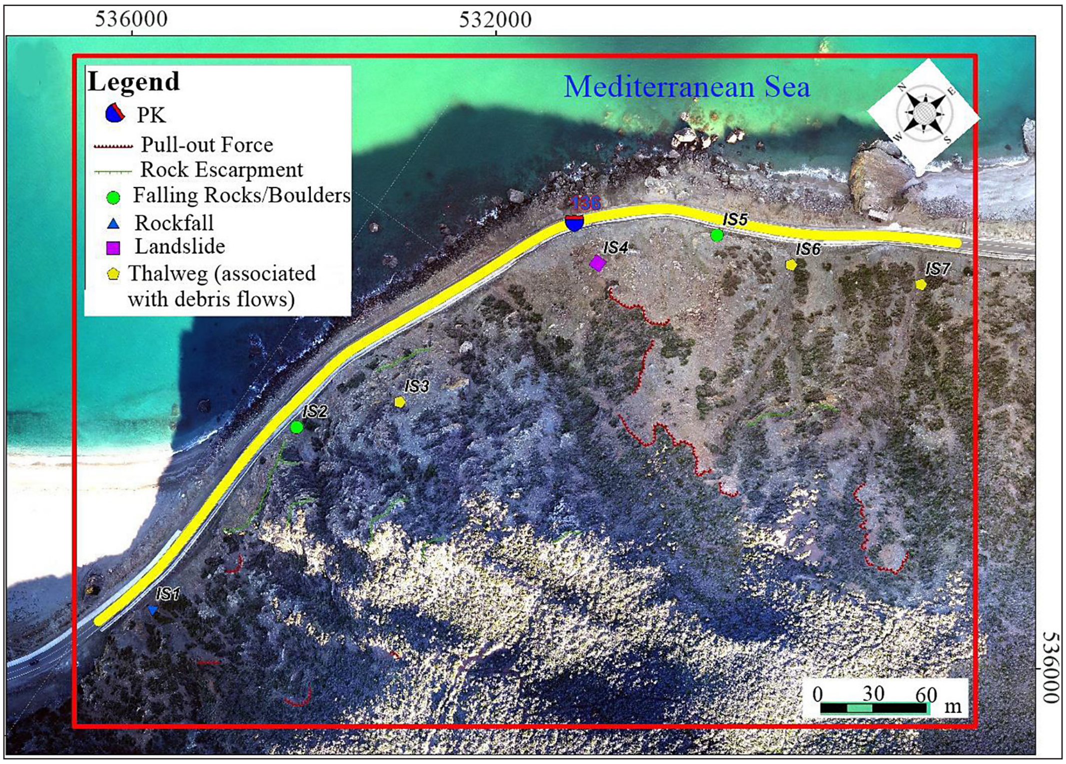


Figure 5. Spatial location of identified instabilities in the study area

valleys exhibiting debris flows. These instabilities cause serious disruptions on the RN16, in addition to frequent traffic stoppages during heavy rainfall (Figure 5).

Based on the analysis of the identified instabilities, it appears that section 2 presents a relatively "major" risk of instability, primarily due to the morphology of the cliff and the directions and dips of the discontinuity planes affecting it, as well as the water infiltration through these discontinuities. It is important to note that this section poses a significant risk to the road (the cliff area has a very steep dip of 70° to 80° and an orientation that seems unfavorable to the stability of blocks delineated by fracturing systems in multiple directions). Therefore, this section is classified as having a very high hazard level.

A risk assessment matrix (Table 1) was developed by the authors to classify the severity and frequency of instability in each section. This matrix integrates field observations of 29 instability sites (landslides, rockfalls, block falls, and debris flows) with geotechnical modeling results from PHASE 2 (safety factors >1.5 without seismic activity, > 1.1 with seismic activity) and RocFall (rockfall trajectory simulations). The classification criteria were adapted from standard geohazard assessment frameworks (Hungr, 2005) and tailored to the site-specific geological and topographic conditions of the RN16 segment. The analysis highlighted the influence of topography, rainfall, lithology, and structural features on slope instability. Conjugate fractures and discontinuities in the micaschists contribute to block dislocation and subsequent rockfalls.

GEOTECHNICAL MODELING

In this study, geotechnical modeling was conducted using PHASE 2 and RocFall software to evaluate slope stability and rockfall risk at the site. Stability calculations indicated safety factors exceeding 1.5 under static conditions, demonstrating a robust design without seismic activity. Under seismic conditions, the safety factors slightly decreased, remaining above 1.1, which is acceptable for the anticipated loading scenarios. RocFall was employed to simulate the trajectories of potential rockfalls, allowing for a detailed analysis of block movement and impact zones. This comprehensive modeling approach ensures that the design adequately addresses both static and dynamic stability, providing a reliable framework for the proposed protective measures against rockfall hazards.

Simulations have shown that the movement of blocks is strongly linked to the slope of the embankment. Blocks can reach the track from a critical slope. Above this slope, the blocks stop on the embankment. Analysis of the topographical conditions revealed representative profiles along the most dangerous sections, on which simulations of rock movements were carried out. The simulations were performed using RocFall software, which analyzes the trajectories, energies, and velocities of falling rocks (Figure 6). The behavior of the blocks also depends on the nature of the terrain traversed by the trajectory of the blocks. Three areas of supporting terrain were simulated: (i) On the slopes: depending on the geological conditions of compact rock or rocky outcrops. (ii) At the bottom of the embankment: the road platform with a wearing course and adjacent loose materials. (iii) The lower terrace was simulated as ordinary soil, possibly vegetated.

Analysis of the rock structure enabled us to determine the probable size and weight of the blocks that break away from the wall. The minimum size would be between 0 and 10 kg and the maximum size between 900 and 2,400 kg. Several simulations were carried out to assess the impact of the size of the blocks (Table 2). The trajectory simulation results, block stopping zones, and energy measured at the road platform for various block weights are displayed in the accompanying Tables 2.

Analysis of Figure 6 and Table 2 allows us to make the following observations: (i) there is a risk of falling rocks in the study area; (ii) in terms of the profile of the study area, the kinetic energy is even greater (up to 1.000 kJ), but the terrain configuration means that some of the blocks remain on the platform. Nevertheless, this area is considered dangerous.

Table 1. Risk assessment matrix

Section	Degree of risk	Classification
1	0	R
2	II	F
3	I	F
4	II	S
5	0	R

Note: R: rare, S: stabilized, F: frequent, 0: no imminent risk, I: urgent intervention recommended, II: future negative impacts.

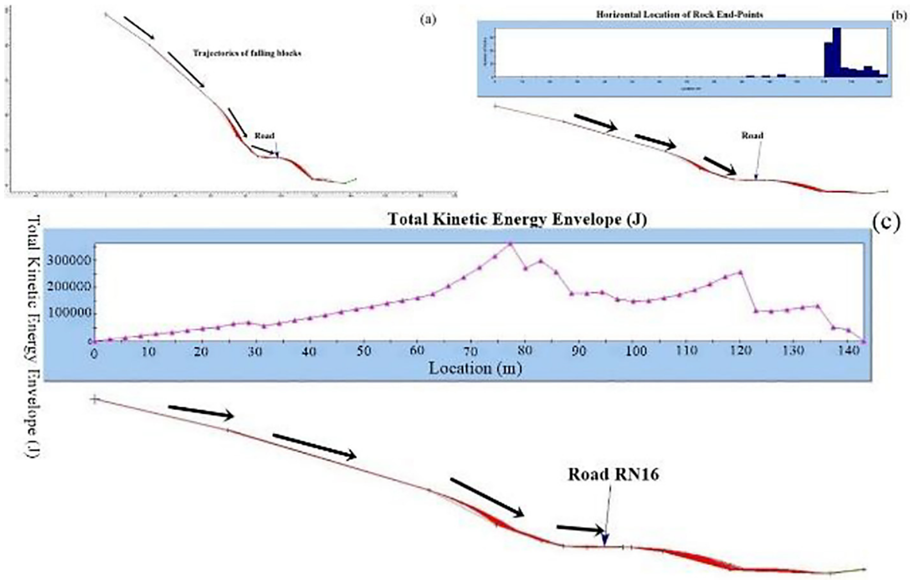


Figure 6. Analysis of rockfall trajectories and kinetic energy impacts along road RN16. (a) trajectories of falling blocks, (b) horizontal location of rock end-points, (c) total kinetic energy envelope (J)

Table 2. Assessment of kinetic energy and block impact risk on roadway in section 2

Profil	Designation	Weight of blocks in kg						
		10	100	500	1000	1500	2000	2400
Section 2	Total kinetic energy (kJ)	1÷3.6	15÷36	70÷270	160÷360	180÷550	250÷810	300÷1000
	Blocks on the road (%)	3	11	8	5	7	7	7

RESULTS

Mechanisms of slope instability

Causal factors

Field missions related to the description and characterization of predefined points have highlighted factors that serve as the driving elements responsible for triggering various disorders and instabilities. In our case, the triggering of a landslide can be linked to the conjunction of several factors, which can be divided into preparatory factors and triggering factors. This makes understanding these factors essential for analyzing and mapping these movements.

Preparatory factors

Geological factors – it is the main preparatory factor in the study area, namely the lithological nature of the slope, the geometry of the materials, and the degree of fracturing (Benzougagh et al., 2020; Riaz et al., 2024). The latter plays a very important role in relation to phenomena such as rockfalls or block falls. Along the studied section, the outcrop is composed of schist formations. For the most part, these formations are covered by loamy-gravelly soils of variable thickness. In some places, the schistosity is very intense, varying from N124 to N169, with an average dip (from 8° to 35°) towards W to SW. This schistosity is accompanied by compressive tectonics, which are manifested in certain sections by decimeter to meter-scale folds, explaining the variation in the direction of schistosity planes on the same plane. The surface materials covering most of the study area are Quaternary deposits of a loamy-gravelly nature, resulting from the weathering of the underlying bedrock.

Topographic factors – encompass several elements, with slope being the most determining factor in the genesis of instabilities, especially for landslides (Lukić et al., 2018; Youssef et al., 2023; El Aoufir et al., 2024). The steeper the slope, the greater the susceptibility of the slope to failure. Considering the topographic aspect is crucial for addressing issues related to erosion and solid transport (Gull et al., 2024; Zhang et al., 2025). Field visits and measurements revealed the presence of steep slopes, with values ranging from 45° to 60°, and even exceeding that for certain schist outcrops (Figure 7). A and B show an example of an unstable slope in the study area, where shale debris fills the ditch, and rockfalls are visible. Solid transport is mainly fed by shale erosion.

Triggering factors

Erosion – veavy rainfall and the denudation of slopes are all factors (plus others) that amplify erosion and the alteration of materials, contributing to the development of gullying phenomena, which can then develop into landslides (Benzougagh et al., 2024; El Brahimi et al., 2024).

Rainfall – precipitation plays a crucial role in triggering landslides in mountainous areas by saturating the soil and increasing its weight, which can destabilize slopes. When heavy rainfall occurs, the water infiltrates the ground, reducing the friction between soil particles and making them more susceptible to movement. This is particularly problematic in steep terrains where gravity exerts a strong force. Additionally, rapid snowmelt can similarly contribute to increased moisture levels, further enhancing the risk of landslides. The combination of these factors can lead to the sudden failure of slopes, resulting in potentially devastating consequences for the surrounding environment and communities (Brahim et al., 2022). With rainfall ranging from 300 to 800 mm in the region, this non-aggressive rainfall may be the result of runoff forces that take over whenever there is enough precipitation to initiate erosion processes.

Anthropogenic action – human activity significantly contributes to the occurrence of landslides through practices such as deforestation, construction, and mining. Deforestation removes the vegetation that stabilizes soil, increasing erosion and making slopes more vulnerable to failure (Maina-Gichaba et al., 2013; Iwuchukwu et al., 2023). Construction activities, particularly on steep terrains, can alter natural drainage patterns and add weight to slopes, further destabilizing them. Additionally, mining operations often disturb the earth, creating loose materials that can easily slide during heavy rainfall or seismic events. These anthropogenic factors can exacerbate natural processes, leading to an increased frequency of landslides and posing risks to nearby communities and infrastructure.

Seismicity – seismicity plays a critical role in triggering landslides, particularly in mountainous and unstable regions. Earthquakes generate ground shaking that can destabilize slopes, causing previously stable materials to shift or collapse (Li et al., 2021; Spiridonov et al., 2025). The intensity and duration of the shaking can lead to the failure of soil and rock layers, especially when they are already saturated from rainfall or other factors. Additionally, seismic activity can create new fractures and weaken existing geological structures, further increasing the risk of landslides. As a result, areas prone to earthquakes often experience a higher incidence of landslides, posing significant hazards to both natural landscapes and human developments.

Based on the causal factors – specifically the preparatory and triggering factors of slope instabilities – an inventory map of instabilities in the study area has been created (Figure 8). The map illustrates an elevation gradient ranging from 0 to 266 meters, indicating a transition from sea level to higher elevations. This gradient may influence erosion and sediment deposition processes in the area. Notably, the map indicates several types of slope movements, including falling rocks, rockfalls, and landslides. These features are marked with specific icons, emphasizing the potential

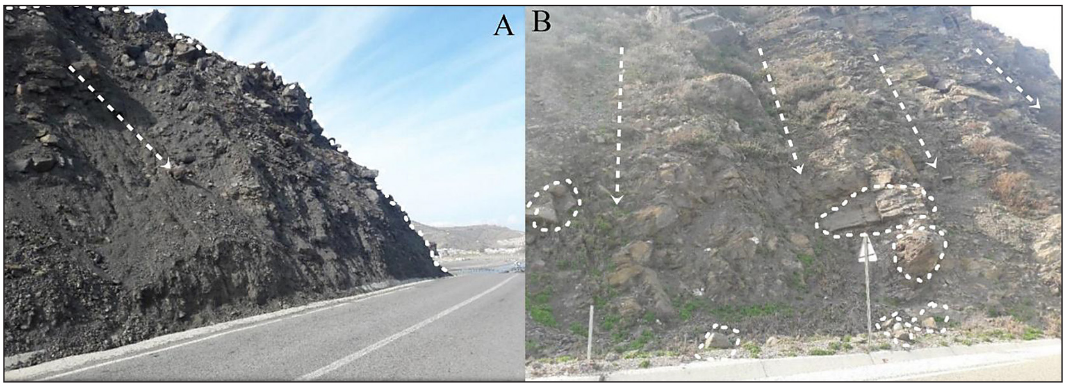


Figure 7. Example of an unstable slope in the study area

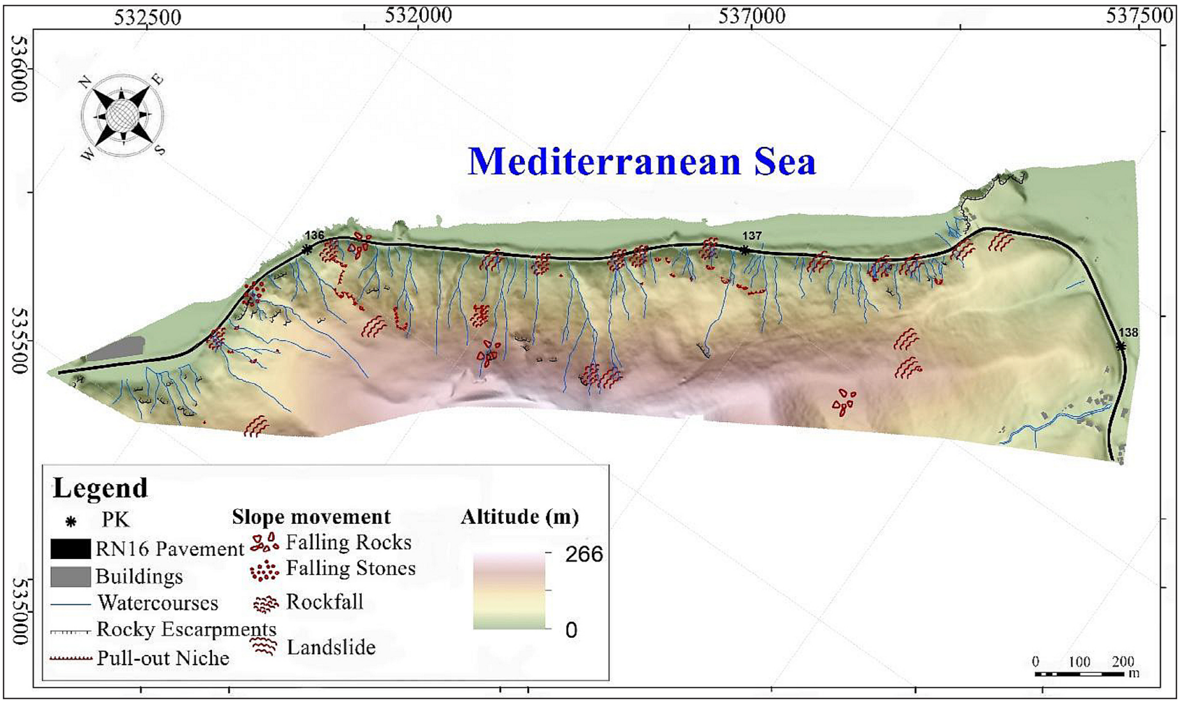


Figure 8. Map of inventoried instabilities in the study area

hazards associated with unstable slopes. structures, such as buildings and watercourses, are also present, illustrating the interaction between human activity and the natural environment. This raises concerns about the vulnerability of these structures to natural hazards like rockfalls and landslides. The RN16 Pavement, a major road depicted on the map, is particularly significant as its proximity to areas of slope movement underscores the importance of infrastructure planning and safety assessments.

Stabilization solutions

The objective of this study is to provide a set of solutions, taking into account geological and geomorphological conditions of study area. In accordance with the results of the diagnostic study presented above and following the trajectory analysis, the aim is to make the section of the RN16 under study safer through various solutions. Based on the instability diagnosis, several stabilization solutions were considered: (i) tunneling – a comprehensive solution involving a tunnel traversing the entire cliff; (ii) false tunnel – a linear structure providing a roof over the road to absorb rockfall impacts; (iii) mesh systems – high-strength wire mesh anchored to the slope to contain unstable areas; (iv) rockfall barriers – structures designed to intercept falling rocks and blocks; (v) slope reshaping – reducing slope angles to improve stability, combined with shotcrete or mesh protection; (vi) debris flow barriers – flexible barriers to protect against solid material transport, (vii) other measures – including slope cleaning, gabion walls, and drainage improvements.

Section 2 interventions

In study area four variants were proposed for Section 2. Variant 1 – a 656.5 m long tunnel bypassing the unstable section. Variant 2 – false tunnel – a concrete structure covering the roadway. The structure was designed as an open frame with a wall on the slope side and support pillars on the opposite side. A layer of calibrated material (0.5–1.5 m thick) would be placed on top to absorb impacts. Variant 3 – mesh and rockfall barriers, involves slope cleaning – a mesh system anchored with bolts, and rockfall barriers. The mesh system would consist of high-strength cable mesh (HEA250) and steel grid (Steelgrid HR30), secured with 25 mm diameter steel bars. Rockfall barriers would be placed to intercept falling blocks. Variant 4 – slope reshaping – reducing the slope angle to 0.25 H/1V, with 5 m high terraces and 4 m wide berms, combined with shotcrete and anchoring.

Stability calculations using PHASE 2 software indicated that the overall slope stability was assured (safety factors > 1.5 without seismic activity and > 1.1 with seismic activity). However, the formation of sliding wedges due to fracturing remained a concern. ROCKFALL software was used to simulate rockfall trajectories and determine appropriate barrier heights and energy absorption capacities.

Solution 1: tunnel

This consists of a comprehensive solution in the form of a tunnel that will cross the entire cliff from the first bend coming from Targha to the center of Azenti. In this case, given the layout of the joints and fractures affecting the rock, digging the tunnel into the massif will cause a release of stress on the front, creating a deformation field with vectors oriented towards the excavation.

Solution 2: false tunnel

It concerns areas with high stakes; steep and cracked cliffs (rocky escarpments). The false tunnel is a passive protection system designed to absorb impacts and deflect rockfall trajectories. This solution is based on gallery protection, supplemented by variants such as anchors, wire mesh cladding, and concrete buttresses at points of instability that could exceed the gallery's stopping capacity. Like all solutions, this one also includes monitoring large, potentially unstable rock masses. Given the available space, the construction of the structure will require earthworks on the cliffs, as well as hydraulic modifications to preserve the continuity of the drainage ditches at the foot of the wall (Figure 9).

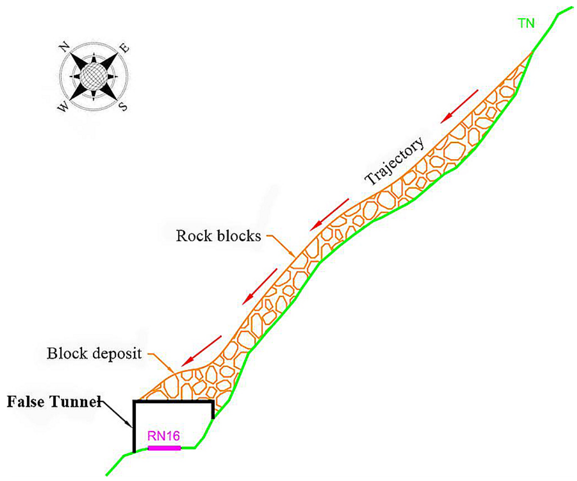


Figure 9. Typical cross-section on Section 2 for Solution 2 (false tunnel)

Solution 3: drainage

Poor drainage of runoff from the cliff slope remains one of the main problems at most of the sites surveyed. It causes intense erosion of the slopes, landslides, and rockfalls. Therefore, to protect against the solid deposits from the chaâbas and their effects on the road, the following measures could be considered (Figure 10): (i) position flexible debris flow barriers (anti-flow), (ii) improve drainage

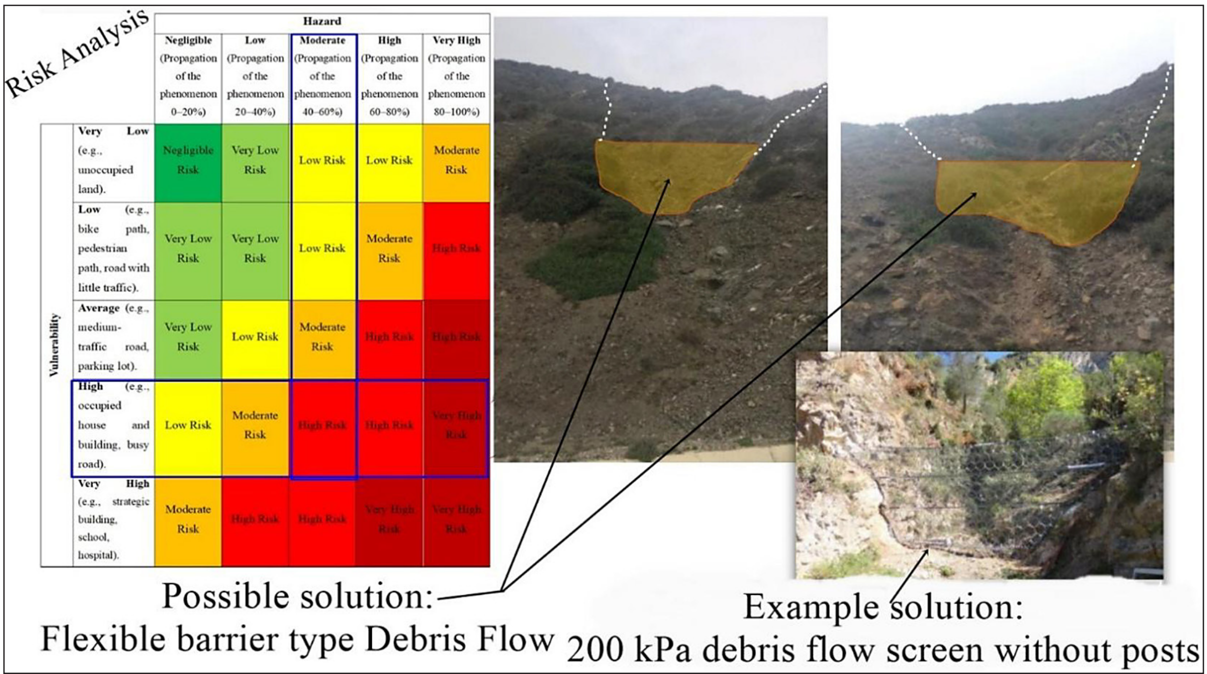


Figure 10. Solution for thalwegs with the possibility of debris flows

of the platform and embankments by constructing concrete ditches, drainage spurs, (iii) install drainage structures at points where there is a risk of water accumulation, or in areas characterized by large volumes of sediment reaching the platform: in this case, the capacity and dimensions of the structure will be justified not only by the flow rate but also by the rate of sediment drained by the chaabas.

Solution 4: retouching

This solution consists of re-sloping and draining the embankment, with the new slopes depending on the geological conditions. In addition to softening the slope, berms will be used for embankments exceeding 7 meters in height, and drainage ditches will be installed at each step. It should be noted that this solution must be combined with the installation of shotcrete + nails, which will be solution 3-1, or the installation of wire mesh + nails, which will be solution 3-2 (Figure 11).

Solution 5: rock screens (rock traps)

The purpose of this intervention is to intercept stones and blocks coming from the slopes (Figure 12 and 13). They must be installed at the foot of cliffs (or rocky escarpments).

Solution 6: cliff reinforcement

This is a mesh panel attached to the walls by an anchoring system. At the level of the cliffs

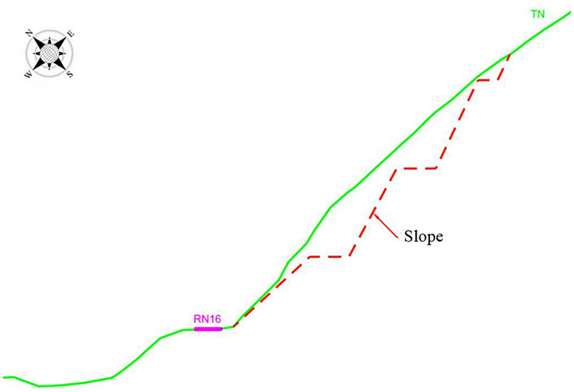


Figure 11. Typical cross-section for solution 4 (re-sloping)

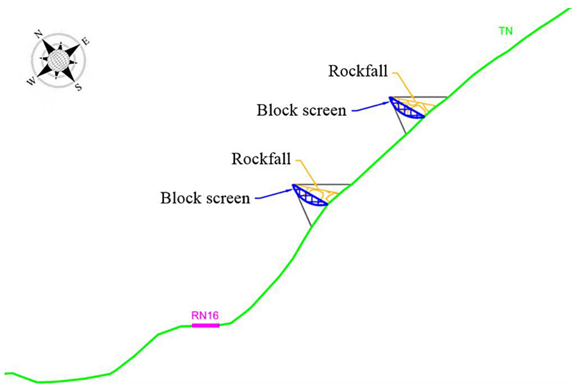


Figure 12. Typical cross-section for solution 5 (tock screens)

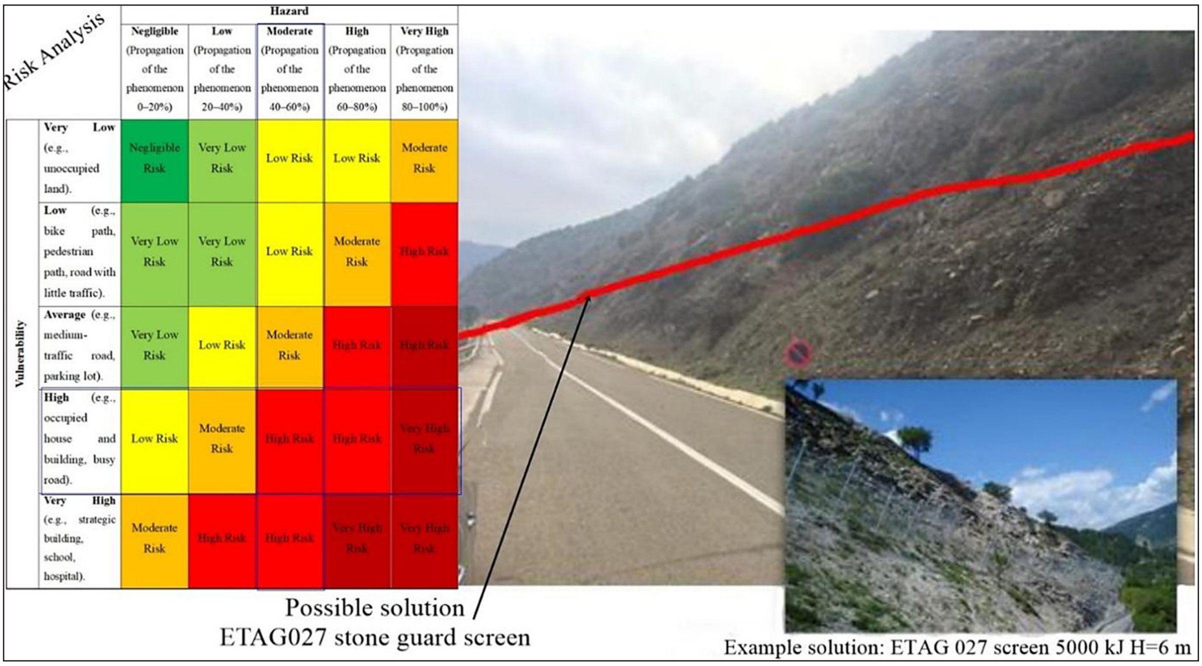


Figure 13. Solution for slopes with a fairly regular gradient and numerous unstable blocks

overlooking the road and at the level of the slope, the mesh panel helps to contain the highly altered and fractured areas of the cliffs (Figure 14 and 15). It is designed to prevent rockfalls from areas that cannot be directly reinforced. Anchor bolts serve two purposes: firstly, to hold and secure mesh panels on unstable rock faces (fixing and securing anchors) and, secondly, to reinforce potentially unstable rock blocks (reinforcing anchors).

Solution 7: anti-erosion

On slopes where there is significant surface erosion, anti-erosion geocomposites could be considered, coupled during manufacture with high-strength mesh (Figure 16).

The study area shows signs of degradation that could have adverse repercussions in the future, with a high degree of intensity and frequent occurrence of such degradation. The study area is prone to rockfalls delimited by discontinuity systems affecting mica schists, and rockfalls of all sizes (from centimeters to meters). Combined re-grading with wire mesh (solutions 4 and 6) will soften the slope and contain the highly weathered and fractured areas to prevent rockfalls. For rockfalls, the installation of rockfall barriers (solution 5) will intercept stones and boulders coming from the slopes. Solutions 2 and 3 remain comprehensive solutions for the entire section. The most suitable solutions are those that provide protection against landslides and rockfalls, which are the causes of various types of damage. It should be noted that solution 1 (tunnel) is a comprehensive solution for the entire section under study.

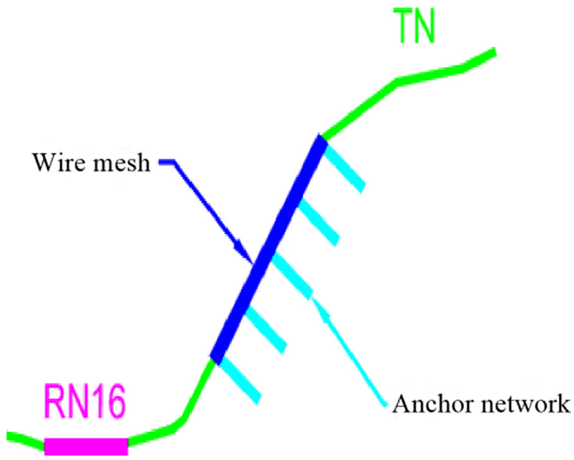
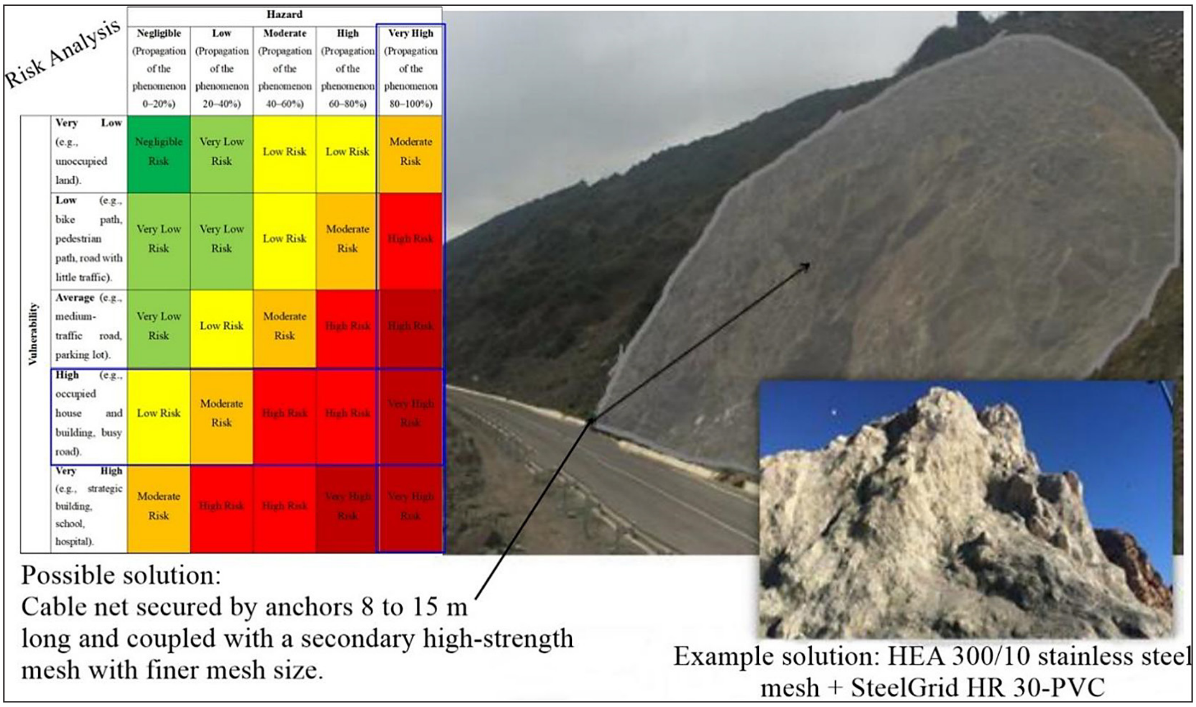


Figure 14. Typical cross-section for solution 6 (cliff reinforcement)

DISCUSSION

The investigation of the RN16 road segment at PK156+000 reveals a complex interplay of geological, topographic, and environmental factors driving slope instability. The dominance of schistose bedrock within the Filali unit, coupled



Risk Analysis	Hazard: Negligible (Propagation of the phenomenon 0–20%)	Low (Propagation of the phenomenon 20–40%)	Moderate (Propagation of the phenomenon 40–60%)	High (Propagation of the phenomenon 60–80%)	Very High (Propagation of the phenomenon 80–100%)
Vulnerability: Very Low (e.g., unoccupied land).	Negligible Risk	Very Low Risk	Low Risk	Low Risk	Moderate Risk
Low (e.g., bike path, pedestrian path, road with little traffic).	Very Low Risk	Very Low Risk	Low Risk	Moderate Risk	High Risk
Average (e.g., medium-traffic road, parking lot).	Very Low Risk	Low Risk	Moderate Risk	High Risk	High Risk
High (e.g., occupied house and building, busy road).	Low Risk	Moderate Risk	High Risk	High Risk	Very High Risk
Very High (e.g., strategic building, school, hospital).	Moderate Risk	High Risk	High Risk	Very High Risk	Very High Risk

Figure 15. Solution for a cliff overhanging the RN 16 highway consisting of highly fractured rock

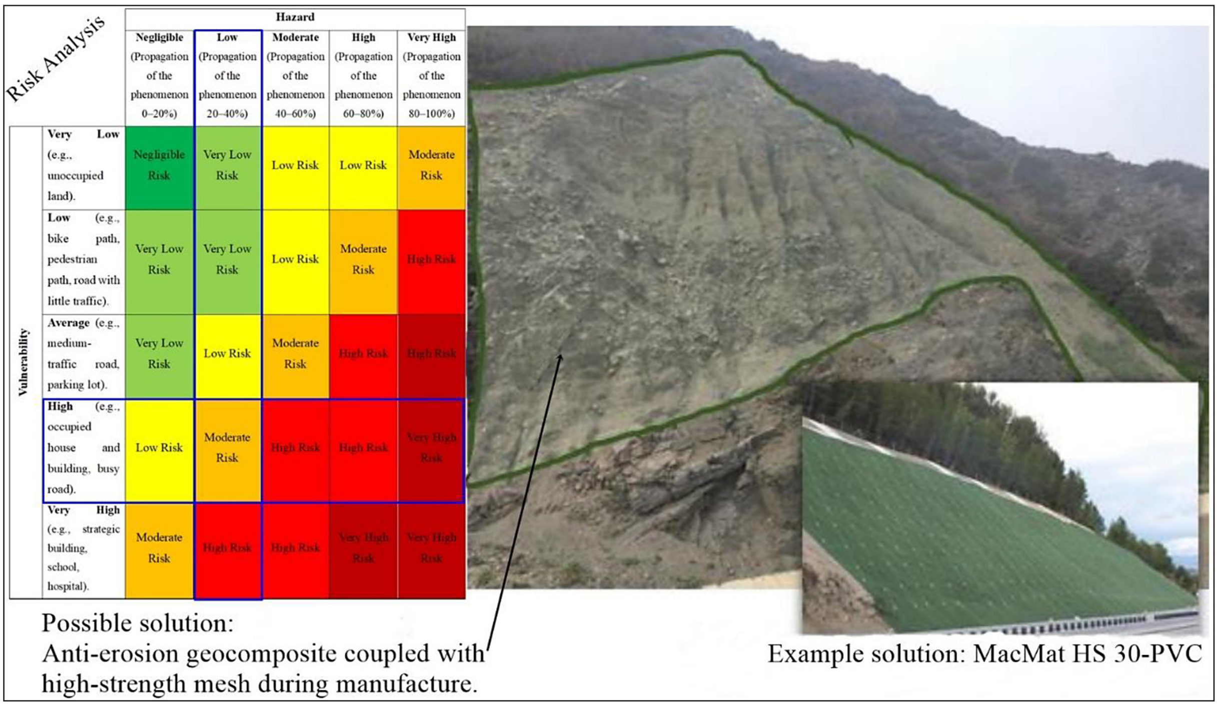


Figure 16. Solution for slopes with severe surface erosion

with a dense network of NE–SW, N–S, and E–W fractures, creates conditions highly conducive to rockfall and landslide events. These structural discontinuities, combined with steep slopes (up to 80°) and seasonal rainfall (300–800 mm annually), exacerbate instability, particularly in Section 2, where quasi-vertical cliffs reach 100 m in height. The identification of 29 instability sites, including rockfalls, block falls, landslides, and debris flows, underscores the urgency of implementing effective mitigation measures to ensure the safety of this critical transportation corridor.

The proposed stabilization variants – tunnels, false tunnels, rockfall nets, gabion walls, and slope reprofiling were evaluated based on geotechnical stability, cost, and long-term durability (Popescu and Zoghi, 2006; Capobianco et al., 2025). Tunnels and false tunnels, while highly effective in shielding the roadway from falling debris, involve significant construction costs and environmental impacts (Li et al., 2022; Lin et al., 2025), particularly in a tectonically active region like the Rif. Conversely, rockfall nets with anchors and slope reprofiling emerged as more cost-effective solutions, offering flexibility and adaptability to the site's heterogeneous lithology and topography (Maheshwari et al., 2023; Rajendra Kumar et al., 2024). The use of gabion walls, while effective for localized stabilization, was found to be less practical for large-scale application due to maintenance requirements and susceptibility to erosion under heavy rainfall (Markiewicz et al., 2024; Naskar et al., 2025). Geotechnical modeling using PHASE 2 and RocFall provided critical insights into the failure mechanisms, particularly the role of conjugate fractures and water infiltration in block dislocation (Zheng et al., 2015; Firoozi et al., 2024). The models highlighted the importance of addressing both preparatory (e.g., lithology, slope angle) and triggering factors (e.g., rainfall, seismicity) in the design process. For instance, the high-risk classification of Section 2 in the risk assessment matrix (Table 1) is attributed to its steep dip (70–80°) and unfavorable fracture orientations, which amplify the potential for block detachment. These findings align with prior studies in similar geological settings, such as those by Assefa et al. (2017) and Benzougagh et al. (2020), which emphasize the role of structural discontinuities in rockfall initiation.

Comparative cost-benefit analyses revealed that a hybrid approach combining rockfall nets and slope reprofiling offers the optimal balance between safety and economic feasibility (Li et al., 2024; Chen et al., 2025). This strategy minimizes disruption to the natural landscape while effectively mitigating hazards. However, challenges remain, including the need for regular maintenance of protective structures and the potential for increased instability due to anthropogenic activities, such as road widening or vegetation removal. Future studies should explore the integration of real-time monitoring systems, such as those proposed by Huanget al. (2025), to enhance early warning capabilities and improve long-term resilience. The broader implications of this study extend beyond the RN16 corridor. The methodological framework, integrating field-based diagnostics, geotechnical modeling, and cost evaluations, provides a scalable model for addressing rockfall hazards in other mountainous regions. By prioritizing cost-effective and environmentally sensitive solutions, this work contributes to the global discourse on sustainable infrastructure development in geohazard-prone areas.

CONCLUSIONS

This study successfully achieved its objectives of characterizing slope instability mechanisms, evaluating stabilization strategies, and developing a scalable framework for mitigating rockfall hazards along the RN16 road at PK156+000 in Chefchaouen, Morocco. Through detailed field-based diagnostics and geotechnical modeling, the research identified 29 instability sites across a 2.5-km cliff segment, with Section 2 classified as having a high hazard level (risk degree II, frequent instability) due to its steep slopes (70–80°) and conjugate fracture systems. Stability calculations using PHASE 2 software confirmed safety factors of > 1.5 (without seismic activity) and > 1.1 (with seismic activity), while RocFall simulations delineated rockfall trajectories, informing the design of protective measures.

The study revealed several novel scientific results. First, it provided a detailed characterization of instability mechanisms in schistose bedrock settings, highlighting the critical role of NE–SW and secondary N–S and E–W fracture networks in block dislocation, a level of detail not previously achieved for the Rif region. Second, comparative analyses demonstrated that a hybrid stabilization approach combining rockfall nets with slope reprofiling offers the optimal balance of cost-effectiveness and geotechnical efficacy, reducing rockfall risks by intercepting blocks and stabilizing slopes. This finding contrasts with prior studies that often prioritized more invasive solutions like tunneling (e.g., Li et al., 2022). Third, the integration of field diagnostics, numerical modeling (Phase 2 and RocFall), and cost-benefit analyses resulted in a comprehensive methodological framework that is both site-specific and scalable, addressing a gap in the literature where such integrated approaches are rare for tectonically active regions with complex lithologies (Maheshwari et al., 2023). This research fills critical knowledge gaps by providing: (1) a site-specific understanding of rockfall drivers in the Rif's schistose terrain, previously underexplored compared to other geological settings; (2) a comparative evaluation of stabilization strategies tailored to heterogeneous lithology and steep topography; and (3) a generalizable framework that combines geological assessments, geotechnical modeling, and economic considerations, which prior studies have not fully integrated (Capobianco et al., 2025). These contributions enhance the scientific understanding of geohazard mitigation in mountainous regions.

The study opens several prospects for future research and application. First, the proposed framework can be adapted to other tectonically active regions, providing a model for engineers and policymakers to design resilient infrastructure. Second, the findings underscore the need for real-time monitoring systems to complement stabilization measures, as suggested by Huang et al. (2025), to enhance early warning capabilities. Third, the hybrid stabilization approach could be further tested in diverse geological settings to validate its scalability. Finally, the research highlights the importance of integrating maintenance and long-term monitoring plans to ensure the durability of protective structures, offering a pathway for sustainable geohazard management. These prospects position the study as a foundation for advancing infrastructure resilience and geotechnical engineering practices globally.

Acknowledgments

The authors would like to express their gratitude to the Provincial Directorate of Equipment, Transport, Logistics, and Water of Chefchaouen (DPETLE) for their invaluable support and collaboration.

REFERENCES

1. Assefa, S., Graziani, A., Lembo-Fazio, A. (2017). A slope movement in a complex rock formation: Deformation measurements and DEM modelling. *Engineering Geology, 219*, 74–91. https://doi.org/10.1016/j.enggeo.2016.10.014

2. Benzougagh, B., Meshram, S. G., Baamar, B., Dridri, A., Boudad, L., Sadkaoui, D., Mimich, K. (2020). Relationship between landslide and morpho-structural analysis: a case study in Northeast of Morocco. *Applied Water Science, 10*(7), 1–10. https://doi.org/10.1007/s13201-020-01258-4
3. Benzougagh, B. et al. (2024). *Spectral Angle Mapper Approach (SAM) for Land Degradation Mapping: A Case Study of the Oued Lahdar Watershed in the Pre-Rif Region (Morocco).* In: Al-Quraishi, A.M.F., Mustafa, Y.T. (eds) Natural Resources Deterioration in MENA Region. Earth and Environmental Sciences Library. Springer, Cham. https://doi.org/10.1007/978-3-031-58315-5_2
4. Bithell, M., Richards, K. S., Bithell, E. G. (2014). Simulation of scree-slope dynamics: investigating the distribution of debris avalanche events in an idealized two-dimensional model. *Earth Surface Processes and Landforms, 39*(12), 1601–1610. https://doi.org/10.1002/esp.3548
5. Brahim, B., Meshram, S. G., Abdallah, D., Larbi, B., Drisss, S., Khalid, M., Khedher, K. M. (2020). Mapping of soil sensitivity to water erosion by RUSLE model: case of the Inaouene watershed (Northeast Morocco). *Arabian Journal of Geosciences, 13*(21), 1153. https://doi.org/10.1007/s12517-020-06079-y
6. Capobianco, V., Choi, C. E., Crosta, G., Hutchinson, D. J., Jaboyedoff, M., Lacasse, S.,..., Reeves, H. (2025). Effective landslide risk management in era of climate change, demographic change, and evolving societal priorities. *Landslides*, 1–19. https://doi.org/10.1007/s10346-024-02418-2
7. Catani, F., Nava, L., Bhuyan, K. (2025). Artificial intelligence applications for landslide mapping and monitoring on EO data. In *Earth Observation Applications to Landslide Mapping, Monitoring and Modeling* 119–145. https://doi.org/10.1016/B978-0-12-823868-4.00007-6
8. Chalouan, A., Michard, A. (2004). The Alpine Rif Belt (Morocco): a case of mountain building in a subduction-subduction-transform fault triple junction. *Pure and applied Geophysics, 161*(3), 489–519. https://doi.org/10.1007/s00024-003-2460-7
9. Chen, B., Maurer, J., Gong, W. (2025). Applications of UAV in landslide research: a review: B. Chen et al. *Landslides*, 1–20. https://doi.org/10.1007/s10346-025-02547-2
10. Cliff, R. A., Bond, C. E., Butler, R. W. H., Dixon, J. E. (2017). Geochronological challenges posed by continuously developing tectonometamorphic systems: insights from Rb–Sr mica ages from the Cycladic Blueschist Belt, Syros (Greece). *Journal of Metamorphic Geology, 35*(2), 197–211. https://doi.org/10.1111/jmg.12228
11. Dahmani, L., Laaribya, S., Naim, H., Tunguz, V., Dindaroglu, T. (2024). Assessing landslide susceptibility in Chefchaouen, Morocco: An application of the landslide numerical risk factor method for sustainable urban development and disaster risk management. *Biosystems Diversity, 32*(3), 389–397. https://doi.org/10.15421/012442
12. El Aoufir, M., Benabbou, M., Benzougagh, B., Sassioui, S., El Asmi, H., Elkourchia, A., Elabouyi, M. (2024). Applying remotely sensed imagery to extract geological lineaments South Rifian Ridges, Morocco. *Ecological Engineering & Environmental Technology, 25*. https://doi.org/10.12912/27197050/188191
13. El Brahimi, M., Mastere, M., Benzougagh, B., El Fellah, B., Fartas, N., Ladel, L.,..., Alluqmani, A. E. (2024). Assessing soil erosion vulnerability through geospatial morphometric analysis in the Oued Amter Basin (Northwest Morocco). *Euro-Mediterranean Journal for Environmental Integration, 9*(3), 1157–1180. https://doi.org/10.1007/s41207-024-00493-4
14. Eze, K. N., Ilesanmi, O. O., Igah, G. C., Abidola, A. Q., Ojefia, F. E., Adekoya, A. M. (2025). Seismic rockfall risk assessments and mitigation strategies for transportation infrastructure in high-risk regions. *Discover Geoscience, 3*(1), 72. https://doi.org/10.1007/s44288-025-00182-x
15. Firoozi, A. A., Firoozi, A. A., Aati, K., Rashid, M. S. (2024). Integrated geotechnical modelling and Real-time analysis for predicting Earthquake-Induced landslides and rockfalls in the East African fracture zone. *Trends Ecol. Indoor Environ. Eng., 2*(3), 1–19. https://doi.org/10.62622/TEIEE.024.2.3.01-19
16. Gull, A., Mahmood, S., Ahamad, M. I., Rehman, A., Purohit, S. (2024). Comparative assessment of Rockfall susceptibility in the Potohar plateau using frequency ratio, analytical hierarchy process, and weights of evidence models. *Earth Systems and Environment,* 1–20. https://doi.org/10.1007/s41748-024-00520-y
17. Hadji, R., Rais, K., Gadri, L., Chouabi, A., Hamed, Y. (2017). Slope failure characteristics and slope movement susceptibility assessment using GIS in a medium scale: a case study from Ouled Driss and Machroha municipalities, Northeast Algeria. *Arabian Journal for Science and Engineering, 42*(1), 281–300. https://doi.org/10.1007/s13369-016-2046-1
18. Hencher, S. R. (2010). Preferential flow paths through soil and rock and their association with landslides. *Hydrological processes, 24*(12), 1610–1630. https://doi.org/10.1002/hyp.7721
19. Hungr, O. (2005). *Classification and terminology*. In Debris-flow hazards and related phenomena 9–23. Berlin, Heidelberg: Springer Berlin Heidelberg. https://doi.org/10.1007/b138657
20. Huang, F., Liu, K., Jiang, S., Catani, F., Liu, W., Fan, X., Huang, J. (2025). Optimization method of conditioning factors selection and combination

for landslide susceptibility prediction. *Journal of Rock Mechanics and Geotechnical Engineering, 17*(2), 722–746. https://doi.org/10.1016/j.jrmge.2024.04.029

21. Iwuchukwu, F.U. et al. (2023). *A Consideration of the Climatic Drivers, Focal Points and Challenges of Soil Erosion, Land Degradation, Landslides and Landscapes in Nigeria.* In: Egbueri, J.C., Ighalo, J.O., Pande, C.B. (eds) Climate Change Impacts on Nigeria. Springer Climate. Springer, Cham. https://doi.org/10.1007/978-3-031-21007-5_23
22. Lakherwal, M., Dhiman, R. K., Thakur, M., Kumar, M. (2024). Kinematic assessment of a rockfall disaster: a case study from Batseri Village, Sangla Valley, Himachal Pradesh, India. *Landslides, 21*(7), 1603–1616. https://doi.org/10.1007/s10346-024-02228-6
23. Leyssens, T., Henry, M., Lambrechts, J., Legat, V., Remacle, J. F. (2025). A coupled PFEM-DEM model for fluid-granular flows with free surface dynamics applied to landslides. *Journal of Computational Physics, 537*, 114082. https://doi.org/10.1016/j.jcp.2025.114082
24. Li, Y. C., Jiang, N., Chen, J. L., Chen, S. Q., Yang, Y. C., Zhou, J. W. (2024). A quantitative optimization method for rockfall passive nets on high-steep slopes: case study of the Feishuiyan slope. *Landslides, 21*(8), 1987–2006. https://doi.org/10.1007/s10346-024-02265-1
25. Li, P., Dai, Z., Huang, D., Cai, W., Fang, T. (2022). Impact analysis for safety prevention and control of special-shaped shield construction closely crossing multiple operational metro tunnels in shallow overburden. *Geotechnical and Geological Engineering, 40*(4), 2127–2144. https://doi.org/10.1007/s10706-021-02016-2
26. Li, F., Torgoev, I., Zaredinov, D., Li, M., Talipov, B., Belousova, A.,..., Schneider, P. (2021). Influence of earthquakes on landslide susceptibility in a seismic prone catchment in central Asia. *Applied Sciences, 11*(9), 3768. https://doi.org/10.3390/app11093768
27. Lin, L., Zhu, H., Ma, Y., Peng, Y., Xia, Y. (2025). Surface feature and defect detection method for shield tunnel based on deep learning. *Journal of Computing in Civil Engineering, 39*(3), 04025019. https://doi.org/10.1061/JCCEE5.CPENG-5986
28. Loew, S., Barla, G., Diederichs, M. (2010, September). *Engineering geology of Alpine tunnels: Past, present and future.* In Geologically active—Proceedings of the 11th IAEG Congress 201–253.
29. Lukić, T., Bjelajac, D., Fitzsimmons, K. E., Marković, S. B., Basarin, B., Mlađan, D.,..., Samardžić, I. (2018). Factors triggering landslide occurrence on the Zemun loess plateau, Belgrade area, Serbia. *Environmental earth sciences, 77*(13), 519. https://doi.org/10.1007/s12665-018-7712-z
30. Maheshwari, S., Bhowmik, R., Samanta, M. (2023). *Rockfall Hazard: A Comprehensive Review of Current Mitigation Practices*. In: Thambidurai, P., Singh, T.N. (eds) Landslides: Detection, Prediction and Monitoring. Springer, Cham. https://doi.org/10.1007/978-3-031-23859-8_9
31. Mahmood, S., Atique, F., Rehman, A., Mayo, S. M., Ahamad, M. I. (2024). Rockfall susceptibility assessment along M-2 motorway in salt range, Pakistan. *Journal of Applied Geophysics, 222*, 105312. https://doi.org/10.1016/j.jappgeo.2024.105312
32. Maina-Gichaba, C., Kipseba, E. K., Masibo, M. (2013). *Overview of landslide occurrences in Kenya: causes, mitigation, and challenges.* In Developments in earth surface processes 16, 293–314. Elsevier. https://doi.org/10.1016/B978-0-444-59559-1.00020-7
33. Markiewicz, A., Koda, E., Kiraga, M., Wrzesiński, G., Kozanka, K., Naliwajko, M., Vaverková, M. D. (2024). Polymeric products in erosion control applications: a review. *Polymers, 16*(17), 2490. https://doi.org/10.3390/polym16172490
34. Mastere, M., El Fellah, B., Maquaire, O. (2020). Landslides inventory map as a first step for hazard and risk assessment: Rif mountains, Morocco. *Bulletin de l'institut Scientifique, Rabat, Section Sciences De La Terre, 42*, 49–62.
35. Naskar, J., Kumar Jha, A., Singh, T. N., Aeron, S. (2025). Climate change and soil resilience: a critical appraisal on innovative techniques for sustainable ground improvement and ecosystem protection. *Journal of Hazardous, Toxic, and Radioactive Waste, 29*(4), 03125002. https://doi.org/10.1061/JHTRBP.HZENG-1465
36. Popescu, M. E., Zoghi, M. (2006). *Landslide risk assessment and remediation.* Craig Taylor & Erik Vanmarcke, Infrastructure Risk Management Processes: Natural, Accidental, and Deliberate Hazards, 161–193.
37. Rajendra Kumar, P., Muthukkumaran, K., Sharma, C. (2024). *Reviewing Slope Stability Integration in Disaster Management and Land Use Planning*. In: Sharma, C., Shukla, A.K., Pathak, S., Singh, V.P. (eds) Sustainable Development and Geospatial Technology. Springer, Cham. https://doi.org/10.1007/978-3-031-65703-0_9
38. Riaz, M. T., Basharat, M., Ahmed, K. S., Sirfraz, Y., Shahzad, A., Shah, N. A. (2024). Failure mechanism of a massive fault–controlled rainfall–triggered landslide in northern Pakistan. *Landslides, 21*(11), 2741–2767. https://doi.org/10.1007/s10346-024-02342-5
39. Spiridonov, V., Ćurić, M., Novkovski, N. (2025). *Exploring Natural Hazards: From Earthquakes, Floods, and Beyond.* In Atmospheric Perspectives: Unveiling Earth's Environmental Challenges 271–306. Cham: Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-86757-6_11
40. Taj, B., MasTere, M., el Fellah, B., Benzougagh, B.

(2023). Apport de la tomographie de la résistivité électrique (TRE) et approche géotechnique pour la caractérisation des instabilités de terrain : Cas du versant de Jebha, Rif, Nord du Maroc. *Bulletin de l'Institut Scientifique, Rabat, Section Sciences de la Terre,* (45), 45–59.

41. Taj, B., Mastere, M., Benzougagh, B., El Hilali, M., Sassioui, S., El Fellah, B. (2024). Geotechnical prospects and electrical tomography to study slope instability in the rif Alboran Sea shoreline on the mediterranean by-road (Northern Morocco). *Ecological Engineering & Environmental Technology, 25*. http://dx.doi.org/10.12912/27197050/174340
42. Wei, D., Wang, C., Zhang, J., Zhao, H., Asakura, Y., Eguchi, M.,..., Yamauchi, Y. (2023). Water activation in solar-powered vapor generation. *Advanced Materials, 35*(47), 2212100. https://doi.org/10.1002/adma.202212100
43. Youssef, B., Bouskri, I., Brahim, B., Kader, S., Brahim, I., Abdelkrim, B., Spalević, V. (2023). The contribution of the frequency ratio model and the prediction rate for the analysis of landslide risk in the Tizi N'tichka area on the national road (RN9) linking Marrakech and Ouarzazate. *Catena, 232*, 107464. https://doi.org/10.1016/j.catena.2023.107464
44. Zhang, K., Gong, Z., Coco, G., Zhao, K., Lanzoni, S. (2025). On the effect of channel slope on seepage-driven bank collapse in tidal channels. *Applied Ocean Research, 161*, 104652. https://doi.org/10.1016/j.apor.2025.104652
45. Zheng, D., Frost, J. D., Huang, R. Q., Liu, F. Z. (2015). Failure process and modes of rockfall induced by underground mining: a case study of Kaiyang Phosphorite Mine rockfalls. *Engineering Geology, 197*, 145–157. https://doi.org/10.1016/j.enggeo.2015.08.011