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Characterization of coastal slope instability: A geophysical and geotechnical study along the Mediterranean ring, Northern Morocco

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ABSTRACT

Natural hazards have become increasingly intense due to the effects of human actions and climate change. Slope instabilities are among the natural disasters that result in loss of life and property. The coastal zones in northern Morocco are recognized for their susceptibility to landslides, primarily attributed to their hilly slopes, tectonic settings, alpine geology, and specific climatic conditions. These factors combine to pose a significant threat to the local population and socio-economic activities in the region. Electrical resistivity tomography (ERT), methods have been used in this case study, as a non-invasive and cost-effective method to characterize subsurface geological properties. We combined the ERT result with geotechnical tests to fill this knowledge gap and gain a better understanding of landslide slope dynamics within their regional context. The results reveal that the platform is experiencing a significant rotational landslide, moving from the base of the slope toward the sea, with slip surfaces located at a depth of approximately 16 meters. Water infiltration through fracture planes acts as a lubricant, contributing to the initiation and reactivation of sliding. Additionally, anthropogenic factors, such as slope degradation from road construction, played a significant role in triggering the observed landslide. The use of both techniques holds great potential for improving interpretation accuracy, particularly in addressing the complexities of near-surface heterogeneity. This approach allows for a more reliable and quantitative evaluation of coastal landslide hazards along the Mediterranean shoreline, paving the way for improved risk management strategies.

Keyword: coastal slope instability, ERT, geotechnical tests, landslide, Mediterranean shoreline.

INTRODUCTION

Slope instability poses a global challenge, affecting diverse landscapes and regions worldwide. Natural factors can play a part in the initiation and reactivation of ground movements such as geological formations, seismic activity, and climate patterns interact with human activities, to aggravate slope instability (Savi et al., 2021; Olabode and San, 2023). Vulnerable areas reach from mountainous terrains to coastal cliffs, and from rural communities to densely populated urban areas. Addressing slope instability requires a multifaceted approach, encompassing geological surveys, sustainable development practices, and early warning systems.

In Northern Morocco, the instability of coastal slopes arises from a complex interaction of geological, environmental, and human-induced factors. The region's varied landscape, stretching from the Rif Mountains to the Mediterranean coast, is prone to multiple forms of slope instability, such as landslides, rockfalls, and soil erosion (Tribak et al., 2022; Obda et al., 2023; Taj et al., 2023, 2024, Labriki et al., 2025). Geologically, the prevalence of weak rock formations and tectonic activity significantly contributes to this instability. Additionally, intense rainfall events further aggravate the situation. Human activities, including deforestation, road construction, and urban expansion, also play a critical role in destabilizing slopes.

Recent, studies in Northern Morocco have increasingly concentrated on unraveling the mechanisms behind slope instability. These efforts employ a combination of geological mapping, remote sensing technologies, and geophysical and geotechnical analyses to better understand the factors driving slope instability in the region (Es-smairi et al., 2021; Boukhres et al., 2023; Taj et al., 2024). These research initiatives aim to pinpoint high-risk zones and establish early warning systems to reduce the adverse effects of slope instability on local populations and infrastructure. Additionally, there has been a growing emphasis on implementing sustainable land management practices and infrastructure design measures to reduce vulnerability to slope instability hazards.

Along the Mediterranean shorelines, coastal slopes instabilities are widespread and the landscape of the internal Rif coast overlooking the Alboran Sea has been transformed. The reshaping of slopes and the excavation of hills to accommodate the road layout (National Road 16) have led to the creation of several unstable areas, where naturally stable slopes have become highly active, regularly threatening populations and obstructing road traffic. This risk poses direct danger individual, affects transportation, and hampers the sustainable development of the region. Anthropogenic intervention has led to the emergence of significant new landslides that deserve to be studied and documented in future risk maps of the region. Yet, the majority of the hypocenters are concentrated in the Alboran Sea, with seismic activities potentially causing site effects such as landslides and earthquakes (Vernant et al., 2010; El Hilali et al., 2021; El Hilali et al., 2023).

The susceptibility maps produced do not accurately represent the true inclination of coastal slopes because of the insufficient and inappropriate data input. The underlying cause is that the landslide inventories fail to capture the favored occurrence of gravitational processes along coastal slopes due the low resolution or insufficient data used (Obda et al., 2023). It is essential to adopt an approach that emphasizes the correlation between slopes, depth and fractures while incorporating all relevant slope parameters. Given that, the study area adjacent to the road is primarily characterized by important tectonic activity and slope failure (Chalouan et al., 2001).

To address this challenge, comprehensive and detailed information derived from geological field observations, geotechnical tests, and geophysical methods are highly valuable and plays a decisive role in landslide investigations. One of the most widely used geophysical methods for landslide analysis is ERT. ERT is particularly effective for evaluating slope deformations and imaging slip surface geometry, thanks to its numerous advantages, although it does have some limitations. For instance, different geological structures can display similar electrical resistivity values, making it difficult to distinguish between them. This underscores the importance of geotechnical data for calibrating and interpreting ERT results. Combining geotechnical and geophysical approaches reduces both the cost and time required for landslide characterization (Rezaei et al., 2019). This study makes a unique contribution to understanding coastal slope instabilities in Northern Morocco by integrating ERT with geotechnical tests to investigate a significant landslide along National Road 16. This approach not only improves the precision of slope stability assessments but also provides a quantitative evaluation of coastal landslide hazards along the Mediterranean shoreline.

STUDY AREA

Geological and tectonics settings

The Rif is a recent mountainous chain of the Betic-Rifan arc, dating from the early Tertiary era, located in northern Morocco on the western coast of the Mediterranean. Structurally, the Rif chain is subdivided into three major structural and paleogeographic domains. From west to east, we distinguish the external domain, the Flysch domain and the internal domain (Delga et al., 1962; Didon et al., 1973). Our study area is situated in the internal zones characterized by Paleozoic and metamorphic terrains typically of the Sebtides and Ghomarid units (Delga et al., 1962; Chalouan et al., 2008). The Sebtide unit is composed mainly by the micaschistes, genesis and kinzigites associated with mantle peridotite of Beni Bousera (Reuber et al., 1982 and Gueydan et al., 2015). Indeed, this unit is overthrust by the Ghomarides formations, which include greywacke and schist affected by Variscan metamorphism and by weak Alpine recrystallization (Chalouan et al., 2001).

Multiple landslides frequently happen within this area due to the geomorphological characteristics (Fig. 1), particularly in locations influenced by human activities like along the road N16. These landslides display diverse behaviors and result in various types of mass movements, driven by changes in environmental conditions (Harmouzi et al., 2019). In the study area, the Ghomaride unit outcrops are prominent, featuring layers of schist, sandstone, and limestone. These formations are generally impermeable and lack significant aquifer systems (Gueydan et al., 2015; El Bakili et al., 2020). Additionally, the micaschists of the lower Sebtides (Filali unit) play a key role in defining the subsoil stratification. These lithological formations are marked by fractures and weak zones, which contribute to occasional landslides and debris flows in the region (Taj et al., 2024). Analyzing slope instability is complex due to gravitational ground movements influenced by a range of factors, including geological and hydrogeological structures, as well as variations in mechanical properties over time.

Climate aspect

The climatic patterns in Northern Morocco exhibit multiannual cyclic trends akin to those

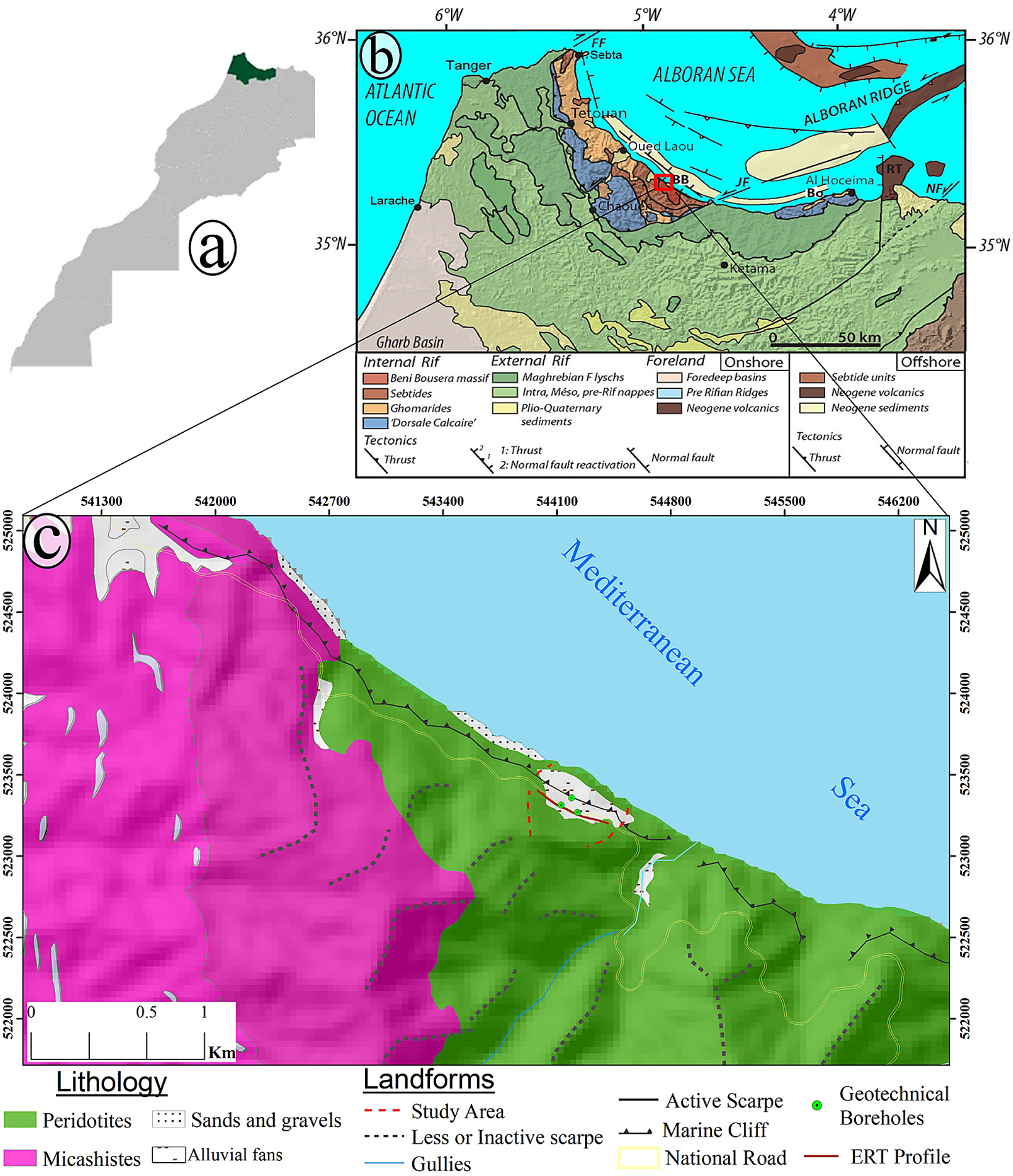

Figure 1. a) Morocco regions Map; b) Tectonic and geological framework of the Rif and southern Alboran Sea (Chalouan and Michard, 1990), c) Lithological and geomorphological maps of the studied landslide with geophysical and geotechnical measurements locations

observed in Southern Spain (Luque-Espinar et al., 2017). On the meteorological aspect, the Mediterranean Sea Shoreline experienced an extended period of increased rainfall from 2009 to 2020. This period, characterized by exceptionally wet winters and springs, resulted in frequent floods and numerous landslides in the region (Notti et al., 2015). Rainfall varies with altitude and exposure of the relief. The average rainfall is around 500 mm per year in a heavy rainy year and it occurs during October-May period (Benabdelouahab et al., 2019).

The torrentially of rainfall occurring on steep slopes invariably triggers the formation of gullies and debris flows, which manifest both at the bottom of the slope and along its length, creating alluvial fans. In this year (2024), the region have a heavy rainfall marked by 198 mm in one day, and induced floods, stop traffic and reactivate new landslides. Average temperatures are generally between 20 and 32 °C in summer, 7, and 22 °C in winter.

The development of marine cliffs and coastal slopes is nearly related to the marine dynamics of the study area due to their exposure to Mediterranean waves. These waves, generated by easterly winds (El Mrini et al., 2012), significantly influence the dynamics of coastal slopes and contribute to the overall evolution of the coastline.

MATERIAL AND METHODS

Geophysical prospection

ERT is a highly effective geophysical technique for evaluating slope stability (Fig. 2). This method operates by mapping variations in the electrical resistivity of subsurface materials. Since resistivity is affected by factors such as moisture content, soil density, and the presence of voids or fractures, these variations can help identify potential weak or unstable zones within a slope. Researchers have combined ERT with geotechnical methods (Fig. 2a) to improve slope monitoring and predict instability more accurately. Previous studies have demonstrated that ERT models are capable of mapping discontinuities and identifying unstable areas at various depths within slopes, making it a powerful tool for assessing landslide risks. (e.g., Perrone et al., 2014; Sun et al., 2024; Taj et al., 2024).

In this study, ERT geophysical measurements were conducted utilizing MAE equipment developed by GF Instruments (Fig. 2b). Different arrays are used for ERT, and each has its merits and demerits. The Wenner-Schlumberger, dipole-dipole, Wenner, and Schlumberger arrays have been widely utilized by researchers in the literature to address slope-related challenges (Guo et al., 2005; Perrone

Figure 2. Site investigation for slope stability analysis: (a) geophysical and geotechnical measurement locations, (b) equipment for electrical resistivity tomography, (c-d) profile alignment along the slope using the Wenner-Schlumberger array

et al., 2014; Falae et al., 2019; Bai et al., 2022; Sassioui et al., 2022). The Wenner-Schlumberger array, known for its sensitivity to vertical structures, maximum depth of penetration, and good resolution, was employed for data collection (Metwaly and AlFouzan, 2013; Falae et al., 2019). It is composed of four collinear current and potential electrodes. The spacing between electrodes was 10 meters and profile measurements were conducted along a 480 m along the Mediterranean road (PK158+000), for the detection of subsurface features to a depth of approximately 52 meters (Fig. 2 c, d).

The field data obtained were initially processed to eliminate bad data points before the inversion process. The interpretation of ERT survey was done by RES2DINV software (Loke and Barker, 1996) to invert the acquired ERT data into inverted pseudosection models using a nonlinear optimization technique with a 2D inversion process. The smoothness-constrain inversion method is a variation of standard inversion techniques, which incorporates a flatness filter. It is particularly well-suited for scenarios where subsurface resistivity undertakes continuous and gradual changes (Pasierb and Gwóźdź, 2019). The standard and similarly smoothness constrain methods, classified as a L2 norm, are based on the least-squared optimization method that minimizes the sum of squares (RMS error) of the spatial changes in the model resistivity values (Loke and Barker, 1996; Loke, 2006). The smoothness constrain inversion method is a slightly modified form of standard inversion including flatness filter and is the most suitable where subsurface resistivity changes continuously in a smooth manner as in the case of pollution plume. The sum of squares is calculated by these methods.

Geotechnical measurements

To achieve a more comprehensive interpretation and analyze the relationship between landslide lithology and the distribution of electrical resistivity along the profile, an in-situ test was conducted using direct measurement techniques (Fig. 3). Additionally, geotechnical surveys were carried out in the landslide area to evaluate ground conditions and determine geotechnical parameters. Inclinometer measurements, collected from sensors installed in boreholes, were used to monitor ground movement, including the direction and magnitude of subsurface lateral displacement at various depths. This data is essential for assessing slope stability and identifying potential landslide risks.

The geotechnical prospecting and reconnaissance program was divided into two parts: First, three core drillings were conducted on either side of the roadway. The core samples obtained were analyzed in the laboratory. These drillings were strategically positioned on both sides of the roadway to study the stability of the platform across its entire width (Fig. 1). Second, the three drillings were equipped with inclinometers to monitor dynamic movements and measure soil mass displacements during the testing period (Table 1).

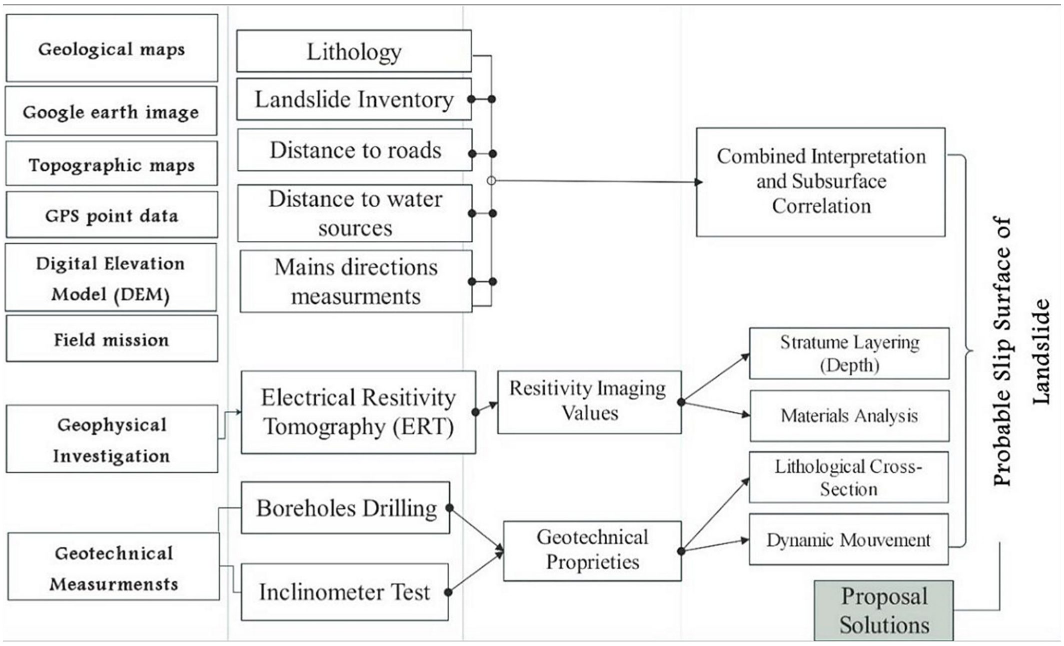

Figure 3. Methodology workflow for subsurface characterization of the landslide

Table 1. Geotechnical measurements

Borehole drilling	Depth (m)	Boreh ole localisation			Inclinometer test	
		X	Y	Elevation (m)	Realized	Duration (days)
B1	40	544.125,69	523.314,78	111	Yes	305
B2	40	544.125,40	523.268,85	106	Yes	304
B3	40	544.190,32	523.359,15	56	Yes	293

Furthermore, the boreholes provided valuable information on soil stratigraphy and groundwater conditions, which were analyzed for their physical and mechanical properties. By combining inclinometer and borehole data, a comprehensive understanding of subsurface conditions and behavior was achieved, enabling the development of safe and cost-effective geotechnical engineering solutions.

RESULTS

In the assessment of slope instability, integrating geotechnical measurements with geophysical surveys provides a thorough understanding of subsurface conditions. This combined approach offers a comprehensive evaluation of slope stability as well as for identifying and addressing potential risks effectively.

Geotechnical results

Analysis of the drill core samples

The boreholes conducted give us a very clear idea of the site's lithology and the presentation of the subsurface layers. The analysis of the initial plates from boreholes SC 1 and SC 2 (Fig. 4) shows that the pavement body rests on a superficial layer of approximately 1 meter, formed by compacted aggregate. Below this layer is a substantial layer that can reach up to 29 meters in some places, mainly composed of small blocks and debris of peridotite embedded in a silty and sometimes clayey matrix of gray to greenish color. In borehole SC 3, this layer appears directly as the upper layer, and the aggregate layer is absent. Beneath this heterogeneous layer, we find the bedrock composed of slightly fractured but relatively intact peridotite (Fig. 5).

Figure 4. The first core sections from drillings B1 and B2 in depth 1 to 5 m

Figure 5. Core section from drilling B2 between 27.50 and 33.50 m

Inclinometer test

The inclinometers were installed in the three boreholes towards the end of November 2019, and the last readings were taken at the end of September 2020. The inclinometer in borehole SC 1 was sheared at a depth of 9.50 meters, but the results obtained at this point were not reliable. For the inclinometer in borehole SC 2, a sudden movement of the probe was observed from 0 to 20 meters in depth (Fig. 5). On the other hand, for borehole SC 3, the inclinometer recorded a gradual movement between 0 and 16 meters with a displacement towards the sea exceeding 60 cm (Fig. 6).

ERT analysis

To enhance our geotechnical analysis of the soil movement on the platform and better understand the observed phenomena, a longitudinal ERT profile was conducted in a historic landslide, approximately four meters away from the observed fracture line on site. The profile of the two-dimensional (2D) resistivity subsurface image is presented in Figure 6.

The ERT profile, characterized by resistivity values ranging from 60 to 1500 ohm-m, provides a comprehensive assessment of the slope's subsurface conditions. High resistivity zones (above 1000 ohm-m) likely correspond to stable ground conditions, potentially indicating bedrock. These areas are generally less susceptible to slope instability. Moderate resistivity zones (300–1000 ohm-m) suggest transitional areas where soil moisture and compaction levels vary. These zones require careful consideration, as they may indicate potential changes in ground conditions that could influence stability.

Low resistivity zones (below 300 ohm-m) are indicative of areas with high moisture content, such as saturated soils or groundwater. These zones are typically associated with an increased risk of slope instability, including erosion, sliding, or slope failure.

The objective of this analysis is to determine whether the ground deformation observed at the base of the slope is due to the vertical collapse of the embankments or if it corresponds to the initial stages of a rotational landslide. These supplementary investigations will enable us to correlate geotechnical data with field observations and propose suitable stabilization solutions. The ERT model obtained (Fig. 7) clearly delineates a rupture surface between 16 and 29 meters, confirming the results of the geotechnical studies. It also provides us with certainty that the movement of the earth forming the platform is developing into a significant rotational landslide, moving from the base of the slope towards the sea.

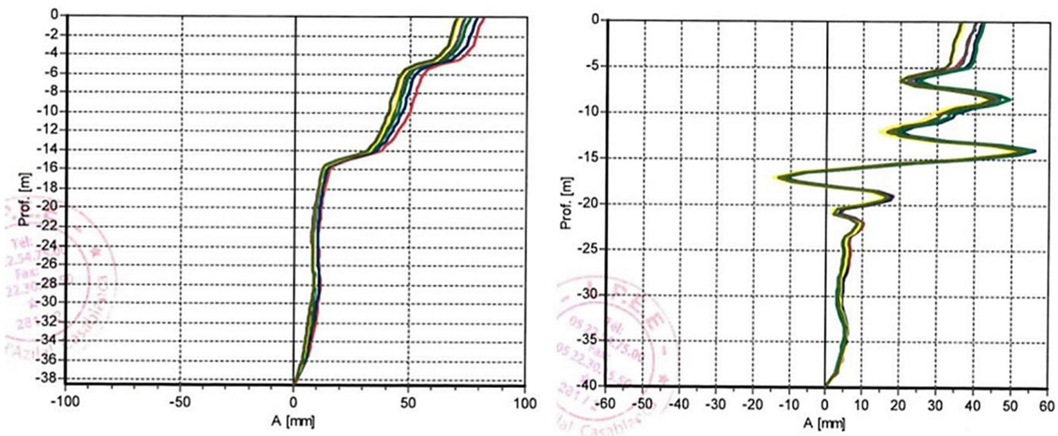

Figure 6. Deformation profile in drilling Borehole 2 (left) and in Borehole 3 (tight)

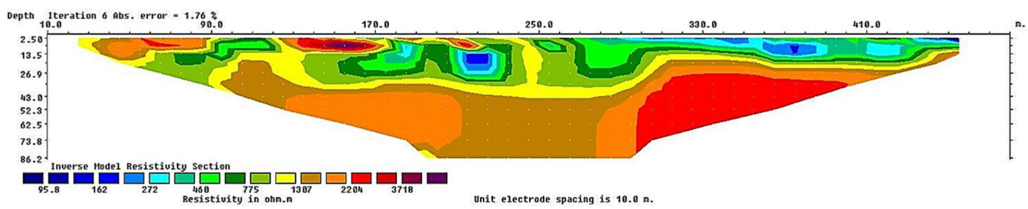

Figure 7. Longitudinal ERT profile implementation and resistivity model obtained

DISCUSSION

The Mediterranean bypass was developed to revitalize the economy of the Mediterranean coast as well as to develop the local economic activities. It is expected to improve accessibility to marginal areas by facilitating access to various services for the population and enhancing the living conditions of the entire region's inhabitants. Beyond the economic aspect, the social dimension of the road is significant. This route, which traverses the entire northern part of Morocco along the Mediterranean shoreline (~527 km), has improved the living conditions of approximately 3 million inhabitants; connected 3 regions, 9 provinces and prefectures, and 8 major cities; provided access to over 200 km of beaches, including the most important ones in northern Morocco (RGPH 2014).

The destabilizing activities of the slopes threaten to undermine the anticipated goals and functions of this strategic route. Recent studies highlight that the coastal slope instabilities in northern Morocco are primarily driven by a combination of geological, hydrological, and anthropogenic factors (Ajraoui et al. 2025). The region's lithology is a significant contributor, with sedimentary rocks such as marl, sandstone, and limestone forming much of the coastal terrain. These rock types are prone to weathering and erosion, which, coupled with the area's complex tectonic activity increases the likelihood of landslides and rockfalls. The proximity to the convergence zone between the African and Eurasian plates adds to the instability, as seismic activity can trigger or worsen slope failures.

Hydrological factors are also critical in influencing slope stability (Fig. 8). The region is subject to heavy seasonal rainfall, particularly during the winter months, which can seep into soil and rock layers, reducing their shear strength and triggering slope failures. Intense rainfall events are particularly significant in initiating such failures. Furthermore, fluvial processes, especially the erosive action of rivers and streams, contribute to slope instability by eroding the base of slopes. This erosion leads to over-steepening and, ultimately, slope collapse.

Anthropogenic factors have increasingly become significant in recent years (Fig. 8). This factor disturb the equilibrium of slopes, making them more prone to failure and alters natural drainage patterns, exacerbating the problem. These human activities have compounded the natural factors, making the slopes more vulnerable to instability. Comparing our findings to previous studies reveals both continuity and change in understanding coastal slope instabilities in Northern Morocco. Bouayad et al. (2010) and El Hmaidi et al. (2015), documented numerous instances of slope failures, attributing them primarily to natural factors like lithology and seismic activity. These studies emphasized the role of the region's geological makeup and tectonic movements in driving slope instability.

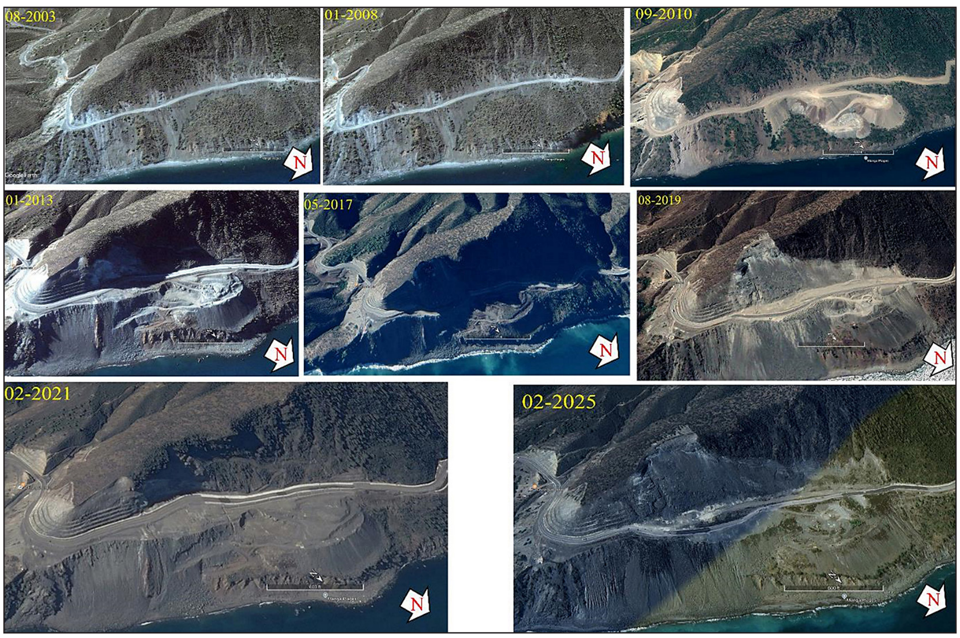

Figure 8. Monitoring the evolution of the studied landslide (2003–2025), using Google Earth Imagery

The Beni Bousera peridotite (Fig. 9) is one such area that has experienced increased landslide activity due to the road construction. Specifically, at kilometer point PK 158+000 of the coastal Mediterranean road, and become highly unstable and is subject to important ground movements and landslides. Even it is an ancient deep movement but still active (Fig. 9). This unstable slope leverages a normal fault plane, but its sliding body exhibits a rotational shape (Fig. 9a). Currently, this area is backfilled. The toe of the landslide is periodically cleared by wave action on a shore platform composed of coarse rubble that covers the peridotite rock mass, which is slightly elevated and in an advanced state of erosion (Fig. 9b). While the primary mechanism involves slow-moving deep-seated landslides, recurrent rockfalls and slides on the cut slopes significantly increase the hazard at this site (Fig. 9c, d, e).

The deformation observed in downhill structures underscores the rotational dynamics of the landslide. This rotational effect is evident when comparing the slopes of the bedding planes within the landslide's foot area to those outside it (Fig. 10). The stereoscopic projection of the plane poles reveals that the bedding planes in the foot area exhibit greater steepness. This steepening is a result of compressional stresses that contribute to the tilting and uplifting of the material in this part of the landslide.

However, we observe that this section of road regularly experiences disruptions in traffic due to ground movements and noticeable deterioration of the pavement. Given that, the initial activity of the embankment occurred during the phase of the ring road development works. Recent publishing work near to our study area, such as Taj et al. (2024), precisely at the PK178+800 indicate that the escarpment is sawn by local faults and fractures which favor the infiltration of water at depth. Also, further weakens the shaly layers substratum and creates new zones of weakness. In addition a recent study by Bounab et al. (2021) observed the mechanisms of deep-seated landslides along the Rifian belt coast, particularly focusing on the schist and greywacke deep-seated landslide and the authors highlighted that the tectonic setting is the primary factor influencing the natural slope dynamics in this coastal hillslope region. Yet, Obda et al. (2023), indicate that coastal slopes are highly prone to gravitational failures despite their rocky composition. Most landslides occur parallel to the coastline, moving towards it. This slope dynamics are influenced by fractures along the coastal fringe (Fig. 10) and the lithological characteristics, shaping the rugged landscape and morphology of these slopes.

Hence, after each period of slope activity, significant quantities of rock blocks and debris were deposited at the base of the slope and overlapping onto the roadway (Es-smairi et al., 2021). The road maintenance services intervened systematically, moving this debris to the other side of the road.

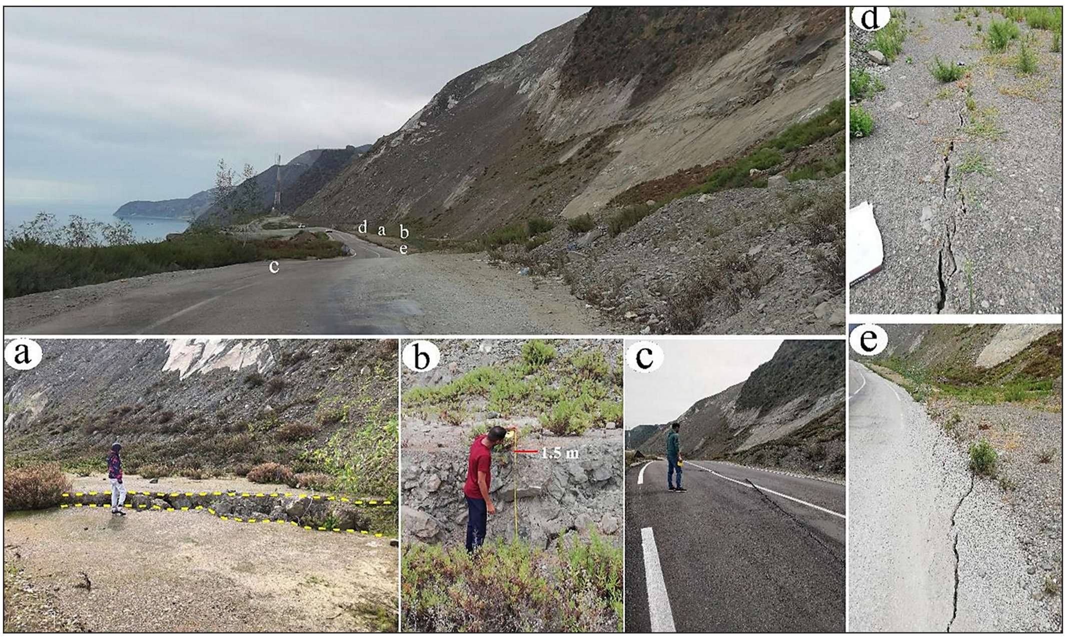

Figure 9. Illustration of some types of anomalies at the studied landslide during the field mission in 2023: (a) detached area, (b) subsided zone (~1.5 m), (c–e) the tension crack in the road and at bottom of the embankment

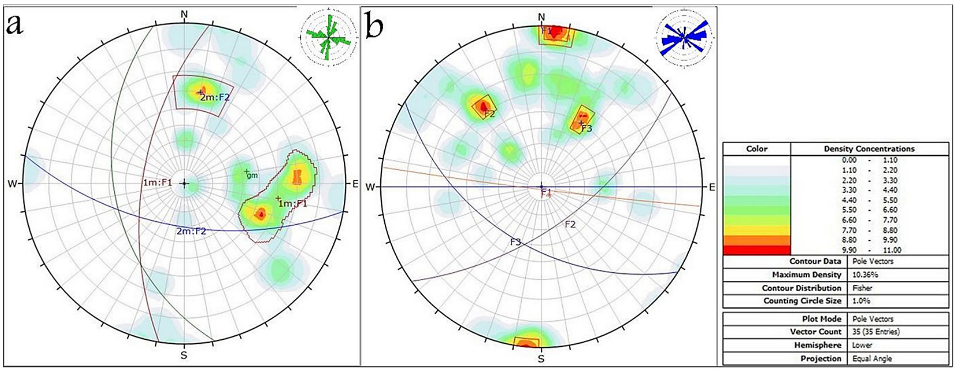

Figure 10. Fracture planes orientations at both the toe of the landslide and in areas beyond it

Due to these loading cycles, successive layers have formed, and the current platform is composed of a large thickness of embankments (up to 29 meters in some places). These volumes of earth have induced significant and unstable overburden, prone to sliding on the natural rupture surface formed by the smooth support of the peridotite.

On the other hand, storms play a key role in marine erosion, progressively eroding mobilizable materials and smoothing the sharp cliffs at the base of coastal slopes (Bounab et al., 2021). This phenomenon is effectively illustrated in our case study that emphasize the morphodynamics of coastal slopes within the study area. These phenomena often result in the development of concave equilibrium shapes that reduce the long shore gradient of erosion or accretion. The main causes of coastal erosion include significant individual storm events and seasonal variations in wave energy and circulation within the near shore shear zone (Snoussi et al., 2009).

ERT has emerged as a critical tool for delineating subsurface characteristics of landslides, particularly in assessing the influence of tectonic structures on landslide geometry and the mechanisms of deep gravitational deformation affecting slope stability. ERT facilitates the identification of subsurface heterogeneities and fault zones that play a significant role in landslide dynamics. Uhlemann et al. (2016) employed ERT to map subsurface resistivity variations, identifying zones of weakness that aligned with tectonic fault lines, thereby demonstrating the direct influence of tectonic features on landslide initiation and progression. Similarly, Sass and Wollny (2001) applied ERT to analyze deep gravitational slope deformations (DGSD), revealing that these deformations were strongly controlled by underlying tectonic structures (Najim et al., 2024), including fault zones and bedrock fractures. In the Betic Cordillera of Southern Spain, Lomas et al. (2017) used ERT to delineate subsurface resistivity profiles and identified multiple fault zones intersecting the landslide body. These fault zones were found to be critical in triggering and shaping the landslide, underscoring the tectonic control on landslide behavior. This approach provided a detailed understanding of deep gravitational mechanics, demonstrating that landslide movements were not limited to surface processes but also involved complex, deep-seated deformations driven by tectonic forces

Similarly, in our case study, ERT was used to detect resistivity contrasts between surface and subsurface layers, aiding in the identification of a significant rotational landslide mechanism. By integrating ERT with geotechnical tests, we established a comprehensive framework for understanding the dynamics of landslide processes. Both approaches emphasize the importance of strategic instrument placement to ensure accurate subsurface characterization.

Limitation of model

The geological complexity of the region, characterized by heterogeneous materials such as varying sediment types and fractured bedrock, can result in ambiguous resistivity contrasts, complicating data interpretation. Surface conditions, including the presence of surface water bodies, can interfere with electrode contact, leading to poor data quality or necessitating extensive preparation (Perrone et al., 2014; Pazzi et al., 2019). While ERT offers good resolution near the surface, its effectiveness decreases with depth (Falae et al., 2019), limiting its ability to accurately image deeper subsurface structures. Our capacity

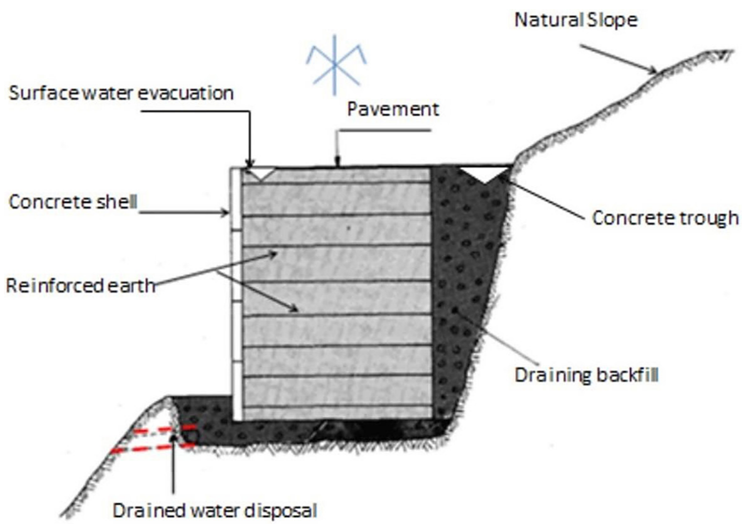

Figure 11. Proposal stabilization solution for the platform using the reinforced earth method

to precisely determine the thickness of weathered layers in certain areas of the landslide and to pinpoint the exact location of the rupture surface was constrained. These challenges highlight the need for complementary methods to enhance the accuracy and reliability of landslide characterization. Although ERT has certain limitations in detecting slope instability, we have effectively addressed these by integrating inclinometer measurements, thereby enhancing our understanding and analysis. Geotechnical measurements provide direct and precise data on subsurface material properties, such as soil strength, cohesion, and friction angle. These measurements offer critical insights into subsurface conditions that ERT alone might either miss or interpret ambiguously.

Proposal solution

To break out of this vicious cycle, it is crucial to find effective and permanent solutions to address slope instability issues and ensure smooth, safe, and continuous traffic flow. It should be noted that in the event of natural disasters such as heavy rainfall or earthquakes, the currently unstable slopes are likely to become active, triggering landslides. Rock falls and debris could block the roadway, hindering the evacuation of victims and the distribution of humanitarian aid to the affected populations.

Before implementing the stabilization solution, it is necessary to reduce the weight of the soil by excavating the embankments and removing the excess soil, particularly that which has been deposited outside the roadway boundaries. The seaward shoulder will be treated by regarding to approximate the slope of the natural terrain. The roadway platform will be restored by backfilling in successive layers following the reinforced earth method, and the embankment body will be strengthened with geo-grids (Fig. 11).

CONCLUSIONS

This study successfully integrates ERT and geotechnical testing to advance our understanding of landslide mechanisms and deliver a comprehensive evaluation of this phenomenon. The combination of these methods yields several key insights and practical applications. ERT has demonstrated its effectiveness in mapping subsurface conditions, revealing variations in soil and rock resistivity that correspond to factors such as moisture content, material type, and the presence of fractures or weak zones. Geotechnical tests provided direct measurements of soil and rock properties, including cohesion and friction angle, which are vital for stability analysis and modeling. Both approaches has pinpointed critical zones within the study area that are particularly susceptible to failure, offering a more robust framework for landslide risk assessment and mitigation. The obtained results confirms that the earth movement shaping the platform is progressing as a substantial rotational landslide, shifting from the slope's base toward the sea, with slip surfaces located approximately 16 meters deep. Water infiltrating and percolating through fracture planes can act as a lubricant, aiding in the initiation and reactivation of sliding movements. Anthropogenic factor, such as the degradation of slopes to construct new roads, played a significant role in triggering the landslide observed in this case study. These findings align with similar studies in northern Morocco, highlighting the effectiveness of ERT in characterizing the interactions between tectonic activity and slope stability. Given the high potential for future landslides in these vulnerable areas, targeted mitigation efforts are essential to reduce associated risks and enhance slope stability.

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