EEET ECOLOGICAL ENGINEERING & ENVIRONMENTAL TECHNOLOGY

Ecological Engineering & Environmental Technology 2024, 25(1), 138–151
https://doi.org/10.12912/27197050/174340
ISSN 2719-7050, License CC-BY 4.0

Received: 2023.10.14
Accepted: 2023.11.18
Published: 2023.12.14

Geotechnical Prospects and Electrical Tomography to Study Slope Instability in the Rif Alboran Sea Shoreline on the Mediterranean By-Road (Northern Morocco)

Benyounes Taj[1], Mohamed Mastere[1], Brahim Benzougagh[1*], Mohamed El Hilali[2], Slimane Sassioui[3], Bouchta El Fellah[1]

[1] Department of Geomorphology and Geomatics, Scientific Institute, Mohammed V University in Rabat, Avenue Ibn Batouta, P.O. Box 703, 10106 Rabat, Morocco

[2] Earth Sciences Department, Scientific Institute, Mohammed V University in Rabat, Rabat, Morocco

[3] Laboratory of Analysis and Modelling of Water and Natural Resources, Mohammadia School of Engineers, Mohammed V University in Rabat, Morocco

* Corresponding author's e-mail: brahim.benzougagh@is.um5.ac.ma

ABSTRACT

The traffic along the Mediterranean ring road in northern Morocco is permanently disrupted by ground movements. Several sections of the road are not available during the rainy period. The slopes and hillsides that were excavated and remodeled during the construction of the roadway have become unstable and are subject to important landslides. In the present study, focused on the section of road located at kilometer point PK 176+800 between Oued Laou and Jebha City. The aim of this study was to evaluate the degree of instability of the studied slope, in the present and to predict it in the future. In situ and laboratory geotechnical tests as well as the geophysical investigations based on Electrical Tomography were carried out to complement the geomatic analyses performed by the research team. The results obtained testify to the effectiveness of the methodology adopted and confirm the threatening instability of the slope studied, in particularly at landslide area.

Keywords: landslide, slope instability, geotechnical, electrical tomography, mediterranean by-road, Northern Morocco.

INTRODUCTION

Studies and publications dealing with landslide hazards in the Moroccan Rif have often focused on classic landslides that were triggered more or less naturally in the past. In fact, Fellah & Mastere (2015), Mastere et al. (2020), and Boukhres et al. (2022) are examples among others. Their dynamics are currently known and their associated risks are relatively well understood.

The development of the Mediterranean (the National 16 or N16) along the northern coast of Morocco began towards the end of the twentieth century and was completed in 2012 (Ministry of Equipment). The earthworks mobilized colossal quantities of cuttings and embankments. The landscape of the inner Rif coast overlooking the Alboran Sea has been transformed. The remodelling of the slopes and the excavation of the hills to follow the road route have caused the creation of several areas of instability, where the naturally stable slopes have become very active and regularly threaten the population and block road traffic. This risk poses a direct threat to people, affects the movement of transport and hinders the sustainable development of the region.

This anthropogenic intervention has given rise to new landslides of significant importance that deserve to be studied and included in the future risk maps of the region. Conducting research studies to map these new landslides, to understand their dynamics and judge their degree of risk, would be of great use by researchers and decision makers, and especially for beneficial to the Moroccan state. In the present study, we focused on the stability of a section of this road, and trying to participate in this reconnaissance campaign of these new landslides.

The studied study area is located in the domain of the inner Rif, at kilometer point PK 176+800 of the Mediterranean road. The choice of this section of road is justified by the importance of the unstable surface of the slope, the consequent morphology of the escarpment and the diversity of ground movements. Also, the availability of recent geotechnical data reinforced the choice. This part of the road is highly degraded, the hydraulic structures are damaged and the majority of the pavement has been carried away by the ground movements. The few attempts to study these new ground movements have been based on the techniques of old investigations based on theory and literature reviews. However, Elmoulat & Ait Brahim (2018), Kassou et al. (2020) and Es-smairi et al. (2021) are the recent examples of these studies.

A scientific diagnostic methodology encompassing geomatics and structural analyses while calling upon geotechnical and geophysical prospection processes as needed is the new research approach followed adopted in this study to understand the dynamics of the active slope and to judge the risk they present for the population and traffic. The aim of this study is to define the causes of instability, the mechanics and geometry of the ground movements in the studied area, and to assess their evolution in order to conclude on the vulnerability of the road to these risks. The investigation techniques used are geotechnical (drilling, Menard tests and inclinometer...) (Plumelle et al. 2017; Brahim et al. 2021; Bouafia 2022), and geophysical investigation by the ERT technique (Bouaziz & Melbouci 2015; Huntley et al. 2019 and Taj et al. 2023), enriched by a geomorphological and geological analysis of the site.

The results obtained show the effectiveness of the geotechnical surveys used to study landslides locally. They provided precise data on the lithology of the terrain and the lines of weakness. Morphological analyses and topographic surveys allowed the definition of the dynamic regime, the unstable volumes and the extent of the risk. The geophysical survey technique ERT-2D is rarely used in the study of landslides in northern Morocco. In the conducted study, it proved to be very useful to define the geometric aspects, the lithological settings and also to detect the zones of high alteration.

The results obtained from this work show that this slope remains threatening. Several parts in this section are unstable and the main landslide at PK 178+800 is developing into a complex landslide currently moving 2 cm seaward each year. Its risk deserves greater mobilization by the authorities in the region. The present study is an important document for decision-makers to implement a comprehensive road infrastructure strengthening and maintenance programme in this section.

GEOGRAPHICAL CONTEXT OF THE STUDY AREA

The section of road studied (Fig. 1) is located on the National 16 (N16), in the province of Chefchaouen, between Jnan Ennich and Amtar, 22 km from Jebha. It is bounded on the one hand by the Mediterranean Sea (on the north side) and on the south side by an imposing hill that marks the landscape with a very steep escarpment and that follows the road for several kilometres.

GEOLOGICAL, TECTONICS AND GEOMORPHOLOGICAL ANALYSIS

The Moroccan 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. According to Durand-Delga et al. (1960), the Rif chain is divided into three domains; internal domain, flysch nappes and the external domain. However, the study area belongs to the internal domain (Ghomarides and the Sebtides units), as shown in Figure 1. Subsequently, the Sebtides units consist of metamorphic rocks of kinzigites and gneisses surrounded by peridotite materials. Consequently, these deposits are overlain by the Quaternary materials deposits, affected by metamorphism tectonic (Farah et al. 2021 and Marrone et al. 2021). Therefore, several major contacts, characteristic of the stacking nappes in the internal zones, which crosse-section the Ghomarides and Sebtides units. The most important one is the Araben fault in the peridotites of Beni Bousera massif (Fig. 1), which brings the peridotites with the Filali micaschists to the SE (Gueydan et al. 2015 and Mourabit Z et

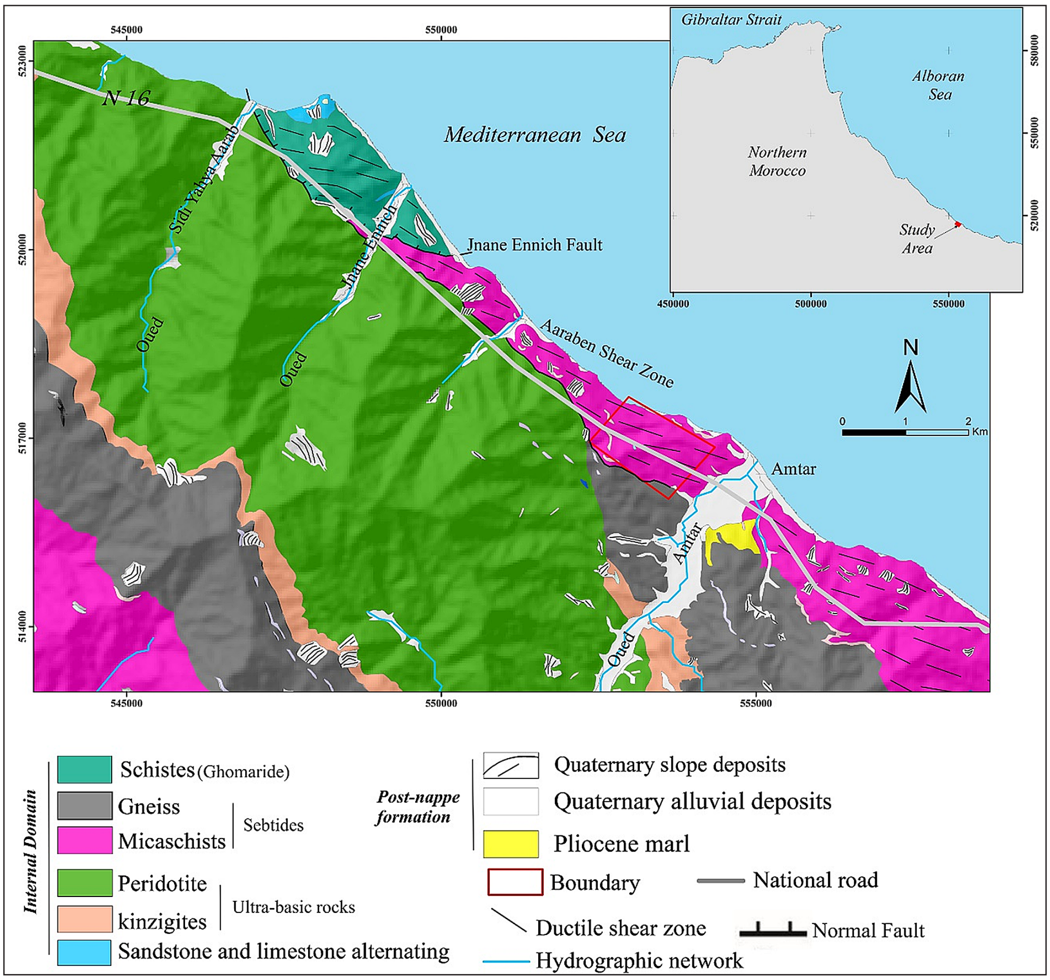

Figure 1. Geological map of the study area

al. 2017), and the Ghomarides to the NW with a vertical thrust. Nevertheless, this contact is often reactivated by small fractured faults accompanied by heavy serpentinisation (Frets et al. 2014).

The stratification of the subsoil is dominated by the Filali micaschist formations (Mourabit et al., 2017). Nevertheless, the Ghomarides units outcrop near to the study area by schist and alternating of sandstone and limestone. These formations are generally impermeable and lack extensive aquifer forms (Gueydan et al., 2014; El Bakili et al., 2020). Moreover, these lithological formations are fractured and have several zones of weakness that induced some typically landslides and debris flow in the area under study. The study of slope instability is delicate due to the gravitational ground movements, which are influenced by many factors such as the geological and hydrogeological structures of the ground as well as the evolution of the mechanical properties of its layers (Bordoni et al. 2015, El Fellah & Mastere 2015).

In fact, the importance of the studied slope instability is defined by its significant geometric characteristics. Actually, the ground moves along the road for a distance of about 1 km. The difference in altitude of this escarpment is 230 m between the highest point and sea level. The roadway is located at a difference in elevation of about 180 m. The average dip is 45°. The surface of the subject area to landslides is approximately 2 Ha. The topographic survey was carried out in September 2020, at a scale of 1/500, illustrating this situation and giving a precise presentation of the relief.

The structural analysis of the discontinuity planes observed on this site allows concluding that the geological formations of this study area are affected by intense fracturation characterized by different families of local faults (fissures and diaclases) with a variable orientation). Although, the deformations observed on the area study are either of a ductile nature exhibited in the anticlinal fold form (Fig. 2B); or in a fractured form associated with the faults (Fig. 2A, 2C).

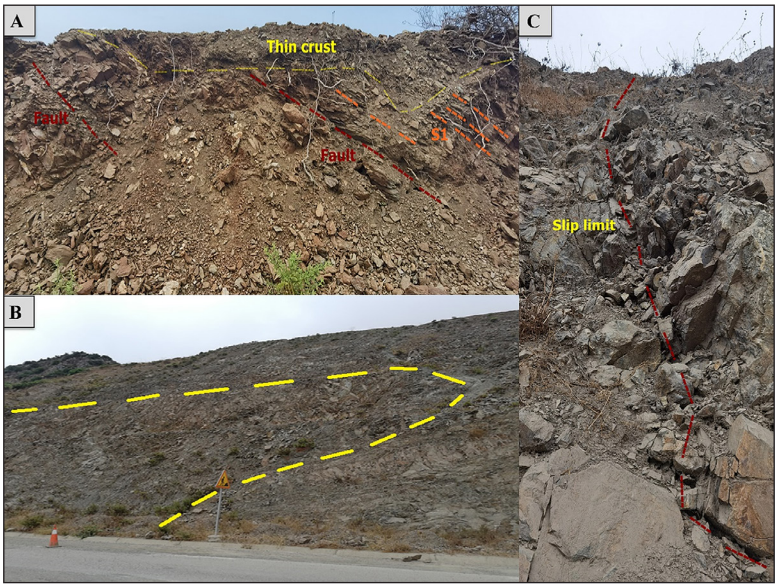

Figure 2. (a) Lithological presentation at the top of the slope, (b) example of an anticlinical fold used on site, (c) fracture marking the limit of the slide

SEISMIC CONTEXT

The catalogue of earthquakes provided by the National Geographic Institute in Spain (IGN), shows that the tangier peninsula is marked by a moderate seismic activity. Yet, most of the hypocenter is concentrated in the Alboran Sea (Vernant et al., 2010; DeMets et al., 2015; Grevemeyer et al., 2015). These seismic activities are likely to induce significant site-effects, such as landslides and earthquakes (El Hilali et al. 2021, 2023). On a regional scale, the catalogue of earthquakes provided by Moroccan institution (CNRST), indicates a preferential earthquakes, which are concentrated in the NW part of the Oued Laou region. This seismic activity propagated from East to West and seems to testify to the present neo-functioning of the two major accidents responsible for the structuration of the region during the Oligo-Miocene era (Cherkaoui & El Hassani 2012).

CLIMATIC ASPECT

The climate of the region is Mediterranean, characterized by a wet and cool winter and a dry and hot summer. Rainfall varies with altitude and exposure of the relief. Average temperatures are generally between 20 and 32°C in summer and 7 and 22°C in winter. The rainfall averages around 500 mm per year in a heavy rainy year. The region is also known for peak daily rainfall of up to 140 mm (Fig. 3).

OVERVIEW OF THE SITUATION

The slope has been visibly modelled by excavation work, creating 4 berms forming stability levels. The two upper levels are not drained and not protected by concrete. These stability platforms are currently highly degraded and have collapsed. The absence of pebble traps to protect the roadway against scree was noted. The crust and vegetation covering the shale bedrock have collapsed, leaving the rock exposed to external degradation (Fig.4A, 4B). This situation has accelerated the degradation of the surface of the slope and accentuated the instabilities. Thus, the shale and micaschist once covered by the protective crust are now exposed to bad weather and extreme temperatures, not to mention the sea air known for its aggressive salinity. The alteration of the rock has facilitated its repeated degradation in each period of winter or following heavy rainfall.

The ground movements in the studied slope can be divided into two zones (Fig. 6): A large part (Zone 1) where the escarpment is subject to relatively recent and local degradation, which for the moment does not affect the road (Fig. 4). The foot of the slope in this zone is remarkably eroded (Fig. 6). A second surface (Zone 2) can be observed where the berms are clearly curved downwards with more significant degradation and scree. Moreover, this last area is limited by cracks and subsidence, suggesting the formation of a complex landslide with clearly defined boundaries (Fig. 6)

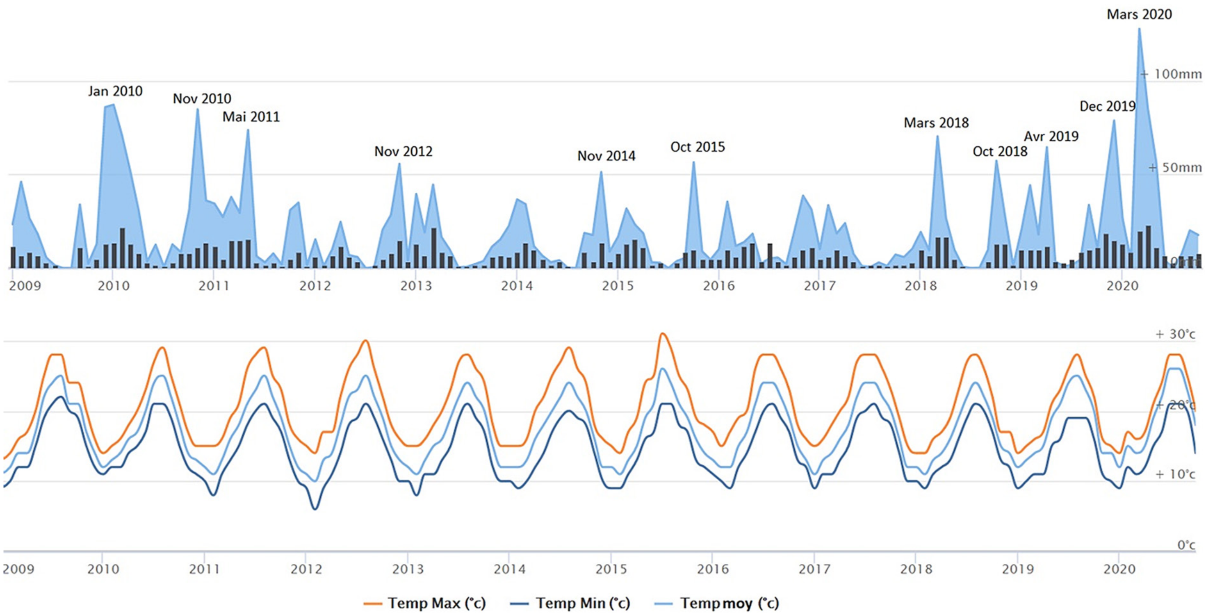

Figure 3. Rainfall and maximum temperatures measured in the counting stations of Afghan, Koudiat Kourirene and Jebha from 2009 to 2020

Figure 4. General overview of the study area

and (Fig. 5). The roadway and the shoulders that cross the landslide area are marked by subsidence and intense cracking, the guardrails are detached and damaged (Fig. 5), which explains that the observed landslide is still active and moving towards the sea. The roadway in this landslide area has collapsed and the hydraulic structure is damaged (Fig. 5.D). The vegetation layer still visible in places on the crest is very thin and is gullied by runoff during each rainfall. This further activates the degradation of the slope and the exposure of the shaly substratum.

MATERIALS AND METHODS

The adopted methodology (Fig. 7) is based on a preliminary study including historical and bibliographical research completed by field surveys and a topographic survey at a scale of 1:5,000.

Figure 5. (a) Cracks and subsidence in the road sides, (b) limit and direction of the slide, (c) crack in the wall of a small house, (d) collapse of the roadway and damaged structures

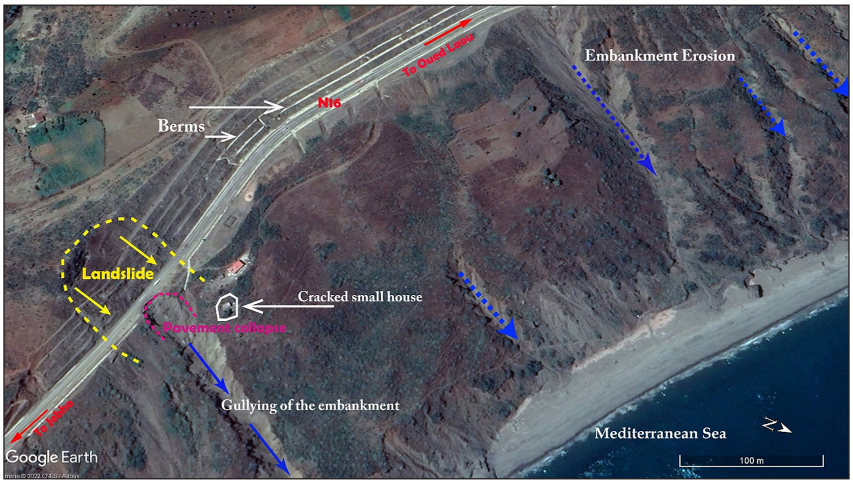

Figure 6. Status of the study area

After this first phase, the geotechnical reconnaissance tests to be carried out either in situ or in the laboratory were defined. Then, the ERT profile was drawn up, according to the needs of the study but taking into consideration the topographical constraints of the terrain. All the geotechnical and geophysical results were analysed and correlated in order to make correct judgement.

GEOTECHNICAL INVESTIGATIONS

In order to identify the various instability mechanisms in the study area and also to have a clearer view of the subsoil formations, geotechnical investigations are of great use (Abdel-Ilah et al., 2022; Bouafia, 2022). In this context, 4 core drillings are distributed on both sides of the roadway in the landslide area, with a fifth at the level of the slope crest (Fig. 8) and (Table 1).

The drill hole and sampling are made according to the standard EN ISO22475-1. The drill cores obtained were analysed visually and also in the laboratory to define the lithology at each depth. Samples of the various layers were taken to the laboratory for triaxial testing and calculation of the specific weights of the various materials The 5 boreholes were used to carry out Menard pressure meter tests to be able to judge the mechanical performance of the different layers and to detect

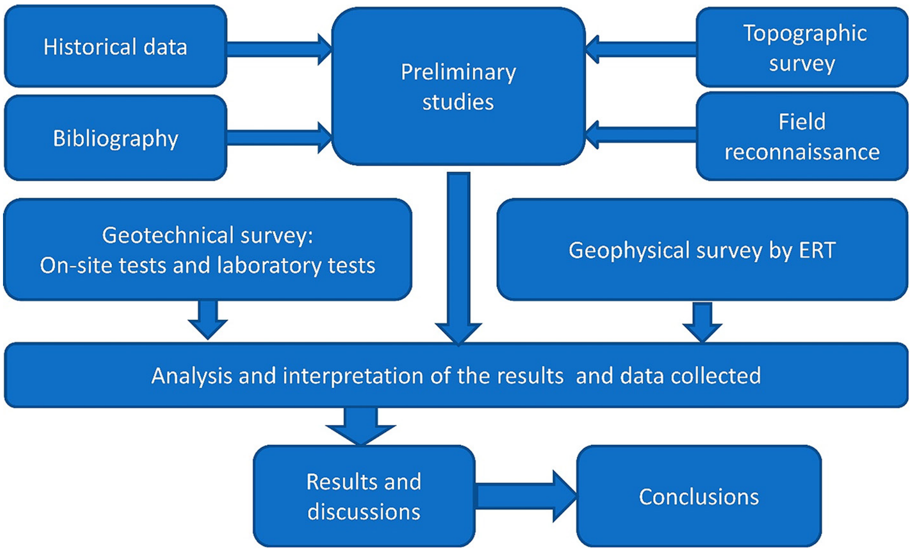

Figure 7. Process and methodology

Table 1. List of boreholes and destination

Drill number	Depth (m)	Menard test	Inclinometer
SCP 1	20	Yes	Yes
SCP 2	20	Yes	Yes
SCP 3	15	Yes	No
SCP 4	30	Yes	Yes
SCP 5	60	Yes	No

possible levels of weakness (Baud & Gambin 2013 and Dos Santos A.L 2022). The tests were carried out using a tri-cellular probe introduced along the borehole; according to the NF P94-110-1 standard. In order to judge the activity and movement of the identified landslide, the core holes SCP1, SCP2 and SCP4, were used to perform inclinometer measurements (Fig. 8) and (Table 1). The inclinometer consists of a mobile waterproof probe 50 cm long, connected to the inextensible cable by a waterproof connector. The contact between the probe and the tube is at least four points. A measurement and data storage system records the position of the low level of the probe guide pin relative to the surface reference mark at the top of the tube. It also measures the inclination of the probe relative to the vertical. The inclinometer used is a GEOKON model GK 604 D, with a digital system. The installation and the follow-up of the results are done according to the NF P94-156 standard.

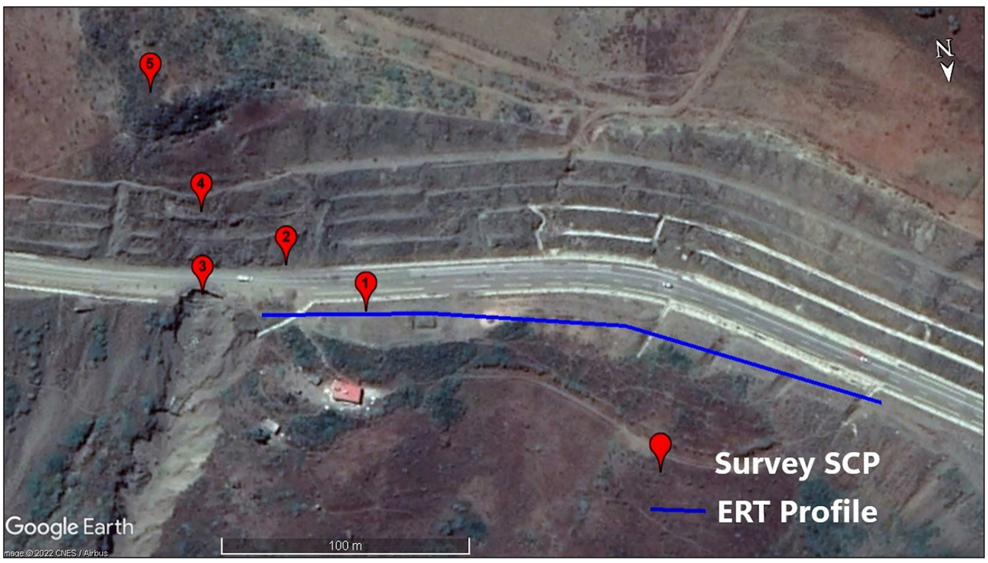

Figure 8. Boreholes and ERT profile location

GEOPHYSICAL SURVEY

The geophisical and geotechnical tests provided a lot of information on the nature of the materials that constitute the body of the escarpment studied. They also allowed understanding its structural, lithological and geological context. However, these results remain relatively punctual and cannot be applied to the whole slope. The geological and geomorphological study allowed exploiting the geotechnical results and making a complete interpretation of the way in which the various formations are set up and also their dynamic behaviour. The use of geophysical prospection means allowed refining the data obtained and to understand the subsoil structures.

The expected objective of the geophysical surveys was to confirm the continuity and consolidation of the shaly substratum in the subsoil, to have a clear idea of the thickness of the weathered surface layer, to check whether there are points of intense weathering and finally to try to understand the disposition of the fractures and cracks observed on the surface. The geophysical survey method used is Electrical Resistivity Tomography (ERT- 2D). It is based on the measurement of apparent electrical resistivity of the subsurface along a set of straight cables connected to a defined number of electrodes, for a large number of positions and spacing of the electrical current injection electrodes and those for the calculation of the potential difference. This geophysical prospecting technique allows for a geological and geometric description of the subsurface based on the resistivity contrast of the formations (Günther & Rücker 2012; Zhou 2018; Sassioui et al. 2022).

Geoelectrical data acquisition was carried out with the MAE "X612EM+" resistivity meter. In order to have a compromise between spatial resolution and depth of investigation, the authors opted for the combined Wegener - Schlumberger device, the distance between the electrodes was fixed at 10 m. The results were evaluated using the zoneres2D software, with an RMS of 6.3% after the fifth iteration. The profile was implanted to the right of the roadway towards Oued Laou following the ENE-WSW orientation, parallel to the topography and perpendicular to the direction of the slide. It also passes next to the core sample SCP1 (Fig. 8). The length of the profile is 220 m; the number of electrodes used is 23.

The regularised least-squares inversion method was used (Zhdanov & Portniaguine, 1999) which is a version of least-squares inversion using a smoothing factor to give a block-smooth distribution model with constant resistivity. Yet, the equation in matrix form for this inversion is as follows:

$$(A^T W^T W A + \mu C^T R C)\Delta m = A^T W^T \Delta f - \mu C^T R C m \quad (1)$$

where: A – a matrix of partial derivatives of apparent resistivity (the Jacobian); C – a smoothing operator; W – a matrix of relative errors of measurements; m – a vector of the model parameters; μ – a regularization parameter; Δf – a vector of deviations between calculated and measured values, R is a tuning factor.

This inversion method is better adapted to the case where the distribution of the resistivity of the soil is very contrasted (case of well-defined limits between geological elements or layers), it enables to give a model which clearly shows the limits of the various layers or contacts which corresponds perfectly to the investigated case, since shale formations crossed by faults or diaclases are explored.

RESULTS AND DISCUSSION

The crust that covers the hill is thin (50-100 cm). This layer is still visible at the crest. It is made up of breccia and shale debris embedded in a brownish clay matrix (Fig. 2A), (Fig. 11) and (Fig. 12). During the construction of the Mediterranean bypass, the slope underwent excavation and demolition work to make way for the road along the planned road layout.

However, to stabilize the new morphology of the slope, 4 berms were built. Only a part of these stability levels is protected by concrete and just one undersized hydraulic structure has been observed in this section, which is made of a DN 1000 concrete nozzle. Currently, this pipe is blocked at the foot of the slope, on the other side; a great part of it is broken and carried away by the landslides (Fig. 5D). Thus, the dominant formation of altered micaschist, folded and fractured along unfavourable cleavage planes (Fig. 2A), have facilitated the infiltration of water and the acceleration of the alteration of the rock.

SYNTHESIS OF GEOTECHNICAL DATA

The analysis of the core samples from SCP1 and SCP2 (Fig. 9) and (Fig. 12), shows that at the level of the roadway, the shaly substratum is reached after about 5 meters of depth. Therefore, a mixture of shale debris and the backfill material forming the pavement body forms of the surface layer. Yet, the greyish shale in the subsoil is heavily fractured and contains whitish calcic seams. In the SCP3 borehole, which is located on the roadway next to the hydraulic structure, it can be seen that the material extracted from the cores consists of backfill material to a depth of around 9 m (Fig. 12). The shale can be identified after this depth, but it is much crushed and is embedded in a greenish or greyish silty-marl matrix. Borehole SCP4, located in the landslide right-of-way, shows a disordered stratification, confirming the structural disorder in this area due to the landslide and the dynamic activity of the slope at this location. At a depth of between 12 m and 15 m, a layer of silty marl, about 2 m thick, can be seen (Fig. 10) (Fig. 12). This layer certainly represents the landslide line and its thickness. The SCP5 borehole (Fig. 11) (Fig. 12), located at the crest of the hill, confirms the small thickness of the crust, not exceeding one meter in thickness. Below this, alternating fractured schistose layers separated by greenish or greyish marl and clayey cleavage joints can be seen, sometimes crossed by white calcic seams. After a depth of about 20 meters, the shale is relatively hard with a decrease in the fracture rate with depth.

Analysis of the results of the Menard pressure-meter tests (according to NF P 94-110-1), carried out in the five boreholes shows that the shaly substratum is consolidated to over-consolidated, but there are zones of altered and fragile weakness at the upper level of borehole SCP4 (Fig. 13), reflecting the development of progressive failure phenomena affecting the slope in the slide zone. Consequently, the deeper layers are much healthier, owing to the deep shale layer which is relatively unaltered and reconstituted by surface movements. In fact, to be able to judge the activity of the observed landslide, inclinometer tests were carried out in boreholes SCP1, SCP2 and SCP4. Although, the tests were carried out in accordance with the NF P 94-156 standard.

Figure 9. The first two core drilling plates SCP 1 & SCP 2: A SCP1 borehole from 0 to 6 m; B SCP1 borehole from 6 to 14 m; C SCP2 borehole from 0 to 9 m; D SCP2 borehole from 9 to 15 m

Figure 10. Core-drilling plates of SCP4 borehole between 12 and 15 m depth

Figure 11. Core-drilling layers of the SCP 5 borehole

The measurements were taken from 17/12/2021 to 06/06/2022. The analysis of the results shows a displacement of the whole in the direction of the sea. This displacement is greater at the level of the inclinometer of borehole SCP4, it is of the order of 10 mm for a period of 6 months, and the slip line is located at a depth of about 10 m (Fig. 14). The deformation is of the order of 1.02° (Fig. 15).

SYNTHESIS OF GEOPHYSICAL DATA

The ERT- 2D model obtained (Fig. 16) confirms the results of SCP1 and SCP2. It indicates that the shale massif that forms the basement structure is homogeneous and forms the entire bedrock of the slope. Also, no voids or groundwater were detected. After a depth of about 10 m, the resistivity in the profile varies between 300 and 800 ohm-m, these

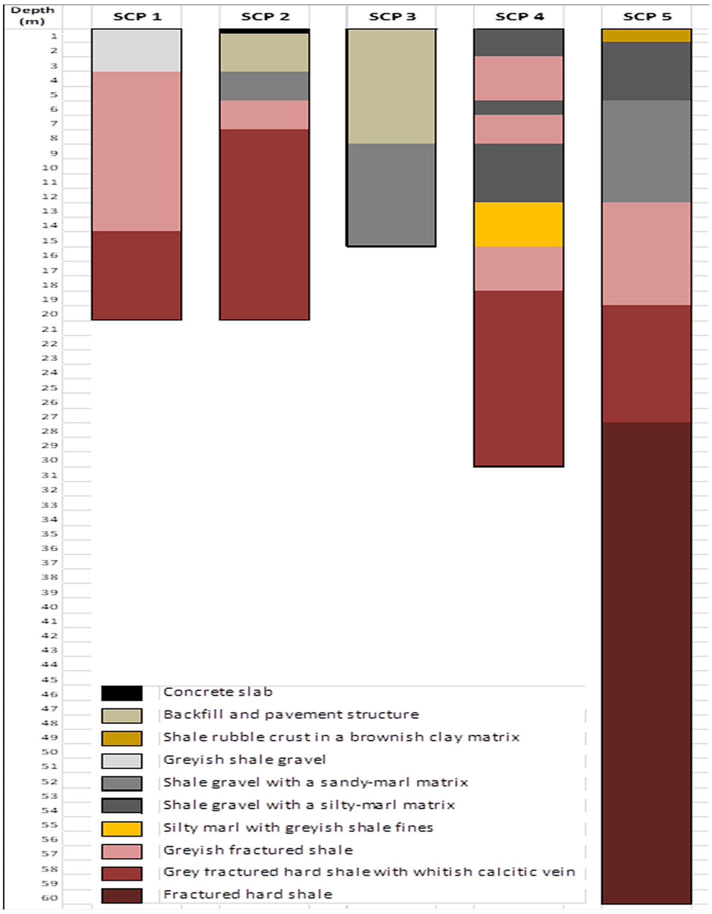

Figure 12. Lithological presentation of the five core-drilling

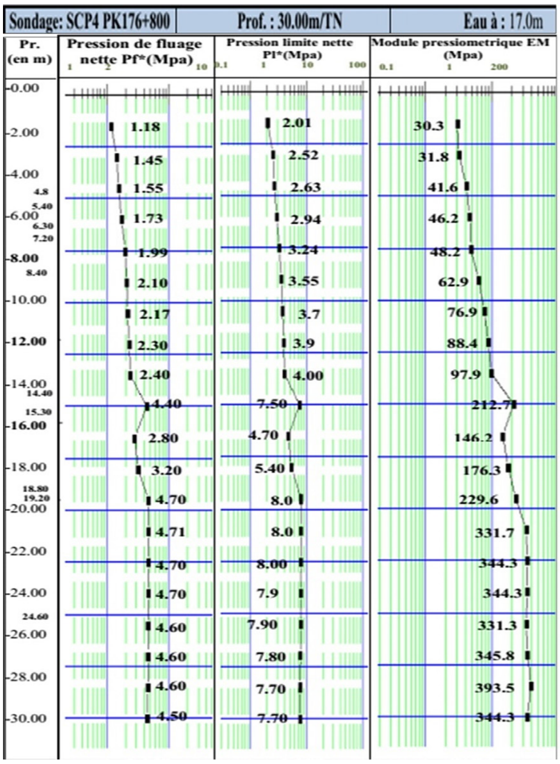

Figure 13. Results of the Menard pressure test at the SCP4 borehole

values have been correlated with the indigenous formations of the site, and confirm the homogeneity of the shaly substratum, which reminds us that we are in a zone of micaschist of the Filali unit. The bedrock has a variable compactness due to its intense fracturing, which explains this variation in resistivity. The profile also shows very wet and weathered surface areas corresponding to the much degraded zones, especially at the beginning of the profile, corresponding to the limits of the landslide.

CONCLUSIONS

The escarpment studied presents several risks of landslides, which can be differentiated according to two categories: A periodic danger linked to landslides that disrupt road traffic during each rainfall or winter period, due to the debris and blocks of rock that slide down the slope, invading the road in the absence of an abutment or pebble trap. Another eminent risk would come from the volume of crushed soil in the landslide right-of-way which is currently in early equilibrium and could rupture at

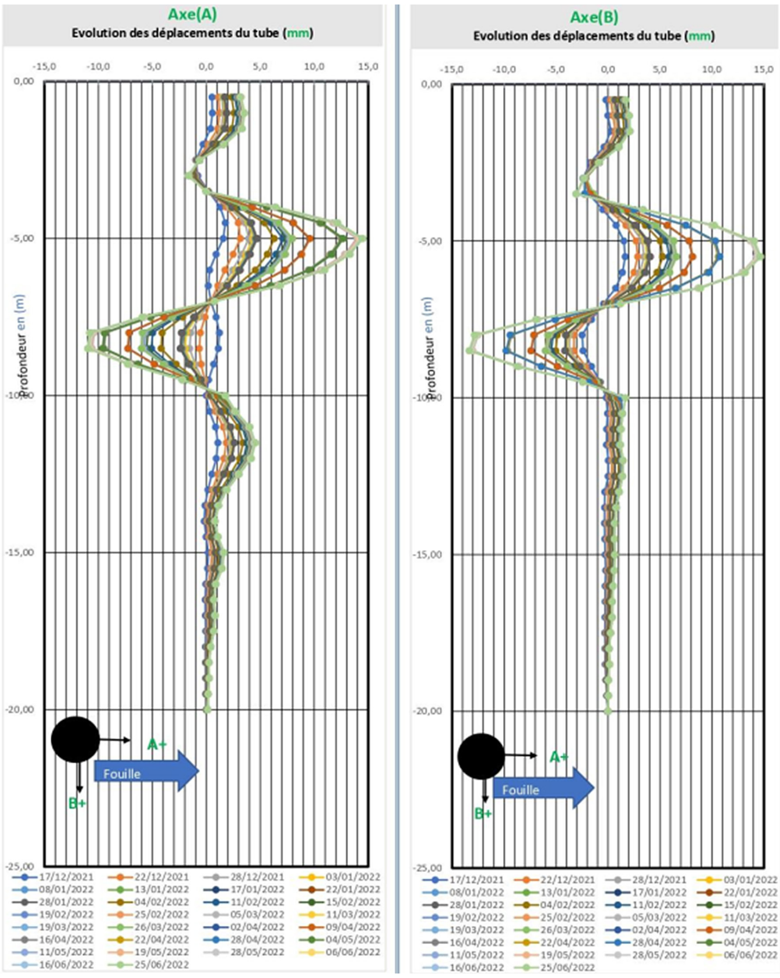

Figure 14. Inclinometer measurements at SCP4 borehole

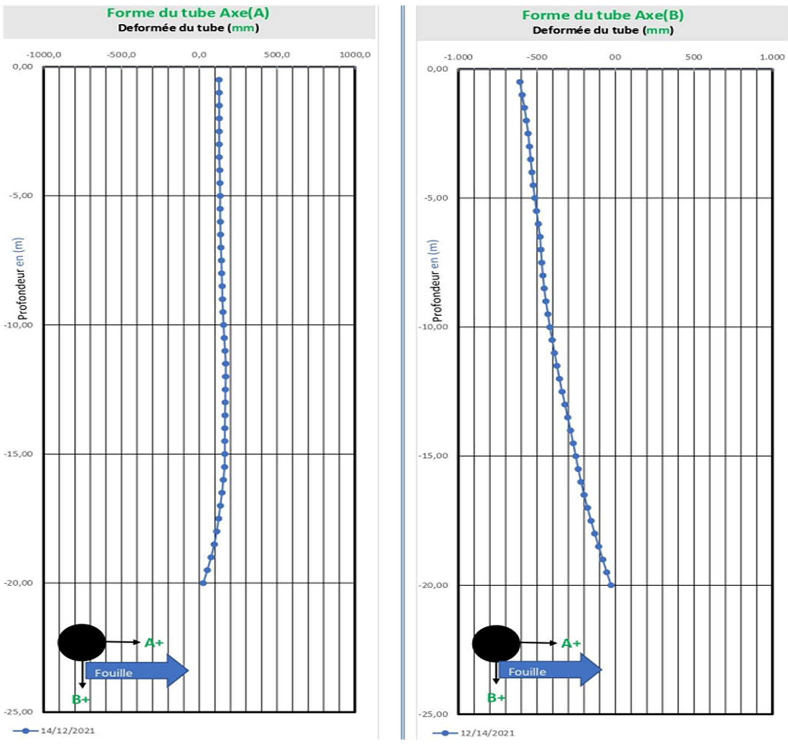

Figure 15. Deformation measurements at the SCP4 borehole

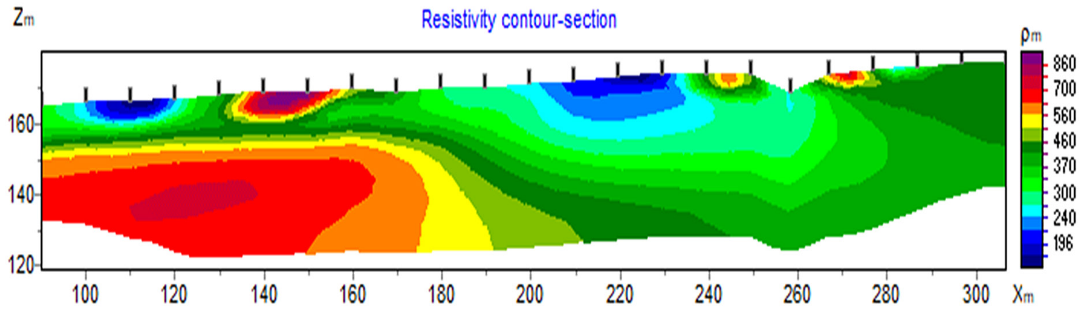

Figure 16. ERT model obtained

any time. This landslide is significant because of the volume of material estimated at 3800 m^3 with an average density calculated in the laboratory of 2.66 tonnes/m^3, i.e. a total mass exceeding 10,000 tonnes. The slope of the slide is dangerously close to the angle of friction calculated in the triaxial test. Finally, this escarpment is sawn by local faults and fractures which favour the infiltration of water at depth. This further weakens the shaly layers substratum and creates new zones of weakness. The section of the road at KP 178+800 is in a threatening state of instability, particularly at the landslide level. The intervention of the competent authorities to address this problem must take into consideration these instabilities in their entirety. The solutions and protective structures to be implemented must take into consideration all the instabilities listed above. In this study, the results obtained by geotechnical and geophysical methods clearly showed the performance of them in slope instability study, mainly for the coastal slopes in northern Morocco, which are not economically developed yet. Hence, these results can be used by different decision makers for the development, in order to avoid unnecessary material damages in the future.

REFERENCES

1. Abdel-Ilah, M., El Kharim, Y., Essaidi, A., Fatima, B., Bazi, A., Bounab, A., 2022. ERT survey and geotechnical characterization of underground cavities: a case study of Amouni coastal cliff, Safi, Morocco. Arabian Journal of Geosciences. 15. https://doi.org/10.1007/s12517-022-10964-z
2. Baud, J.P., Gambin, M., 2013. Détermination du coefficient rhéologique α de Ménard dans le diagramme Pressiorama. In: Proceedings of the 18th International Conference on Soil Mechanics and Geotechnical Engineering, Paris.
3. Bordoni, M., Meisina, C., Valentino, R., Lu, N., Bittelli, M., & Chersich, S. 2015. Hydrological factors affecting rainfall-induced shallow landslides: from the field monitoring to a simplified slope stability analysis. Engineering Geology, 193, 19-37.
4. Bouaziz, N., & Melbouci, B. 2015. Apport de la tomographie électrique à l'étude des glissements de terrains en Grande Kabylie, Algérie. In Rencontres Universitaires de Génie Civil.
5. Brahim, M., Mohammed Hemza, A., Gadouri, H., 2021. Étude des glissements de terrain à l'aide des données géologiques et géotechniques : une étude de cas sur le glissement de terrain de Boufhima (Tizi-Ouzou, Algérie).
6. Břežný, M., Pánek, T., 2017. Deep-seated landslides affecting monoclinal flysch morphostructure: Evaluation of LiDAR-derived topography of the highest range of the Czech Carpathians. Geomorphology 285, 44–57.
7. Cherkaoui, T.E., & El Hassani, A. 2012. Seismicity and Seismic hazard in Morocco. Bulletin de l'Institut Scientifique, Rabat, section Sciences de la Terre, 34, 45-55.
8. CNRST : Centre nationale pour la recherche scientifique et technique. https://www.cnrst.ma
9. DeMets, C., Iaffaldano, G., & Merkouriev, S. 2015. High-resolution Neogene and quaternary estimates of Nubia-Eurasia-North America plate motion. Geophysical Journal International, 203(1), 416-427.
10. Dos Santos, A.L., 2022. Louis Menard et l'essai pressiometrique. Comité Français de Mécanique des Sols et de Géotechnique (CFMS).
11. Durand-Delga, M., Hottinger, L., Marçais, J., Mattauer, M., Milliard, Y., & Suter, G. 1960. Données actuelles sur la structure du Rif. En vente à la Société géologique de France.
12. El Bakili, A., Corsini, M., Chalouan, A., Münch, P., Romagny, A., Lardeaux, J.M., & Azdimousa, A. 2020. Neogene polyphase deformation related to the Alboran Basin evolution: new insights for the Beni Bousera massif (Internal Rif, Morocco). BSGF-Earth Sciences Bulletin, 191(1), 10.
13. El Fellah, B., Mastere, M., 2015. Les côtiers méditerranéens du Rif central: Facteurs induisant l'instabilité

des versants The central Rif Mediterranean coast: Slope failures causative factors. Bulletin de l'Institut Scientifique, Rabat, Section Sciences de la Terre, 35–43.

14. El Hilali, M., Timoulali, Y., Benyounes, T., Ahniche, M., El Bardai, R., & Yattara, S. 2021. Earthquake-induced liquefaction in the coastal zone, Case of Martil city, Morocco. In E3S Web of Conferences (Vol. 298, p. 01002). EDP Sciences.
15. EL Hilali, M., Bounab, A., Timoulali, Y., El Messari, J.E.S., & Ahniche, M. 2023. Seismic site-effects assessment in a fluvial sedimentary environment: case of Oued Martil floodplain, Northern Morocco. Natural Hazards, 1-23.
16. Elmoulat, M., & Ait Brahim, L. 2018. Landslides susceptibility mapping using GIS and weights of evidence model in Tetouan-Ras-Mazari area (Northern Morocco). Geomatics, Natural Hazards and Risk, 9(1), 1306-1325.
17. Falae, P.O., Kanungo, D.P., Chauhan, P.K.S., & Dash, R.K. 2019. Electrical resistivity tomography (ERT) based subsurface characterisation of Pakhi Landslide, Garhwal Himalayas, India. Environmental Earth Sciences, 78(14), 1-18.
18. Farah, A., Michard, A., Saddiqi, O., Chalouan, A., Chopin, C., Montero, P., Corsini, M., Bea, F., 2021. The Beni Bousera marbles, record of a Triassic-Early Jurassic hyperextended margin in the Alpujarrides-Sebtides units (Rif belt, Morocco). BSGF-Earth Sci. Bull. 192, 26.
19. Frets, E.C., Tommasi, A., Garrido, C J., Vauchez, A., Mainprice, D., Targuisti, K., & Amri, I. 2014. The Beni Bousera peridotite (Rif Belt, Morocco): an oblique-slip low-angle shear zone thinning the subcontinental mantle lithosphere. Journal of Petrology, 55(2), 283-313.
20. Grelle, G., Revellino, P., Donnarumma, A., & Guadagno, F.M. 2011. Bedding control on landslides: a methodological approach for computer-aided mapping analysis. Natural Hazards and Earth System Sciences, 11(5), 1395-1409.
21. Grevemeyer, I., Gràcia, E., Villaseñor, A., Leuchters, W., & Watts, A. B. 2015. Seismicity and active tectonics in the Alboran Sea, Western Mediterranean: Constraints from an offshore-onshore seismological network and swath bathymetry data. Journal of Geophysical Research: Solid Earth, 120(12), 8348-8365.
22. Gueydan, F., Précigout, J., Montesi, L. 2014. Strain weakening enables continental plate tectonics. Tectonophysics, 631, 89-196. https://doi.org/10.1016/j.tecto.2014.02.005
23. Gueydan, F., Pitra, P., Afiri, A., Poujol, M., Essaifi, A., & Paquette, J.L. 2015. Oligo-Miocene thinning of the Beni Bousera peridotites and their Variscan crustal host rocks, Internal Rif, Morocco. Tectonics, 34(6), 1244-1268
24. Günther, T., & Rücker, C. 2012. Electrical Resistivity Tomography (ERT) in geophysical applications-state of the art and future challenges. In Schlumberger Symposium--100 years of electrical imaging, Paris.
25. Huntley, D., Bobrowsky, P., Hendry, M., Macciotta, R., & Best, M. 2019. Multi-technique geophysical investigation of a very slow-moving landslide near Ashcroft, British Columbia, Canada. Journal of Environmental and Engineering Geophysics, 24(1), 87-110.
26. IGN: National Geographic Institue; Spanish seismic cataloge.https://doi.org/10.7419/162.03.2022
27. Kassou, F., Bouziyane, J.B., Ghafiri, A., & Sabihi, A. 2020. Slope stability of embankments on soft soil improved with vertical drains. Civil Engineering Journal, 6(1), 164-173
28. Marrone, S., Monié, P., Rossetti, F. et al. 2021. The pressure–temperature–time–deformation history of the Beni Mzala unit (Upper Sebtides, Rif belt, Morocco): Refining the Alpine tectono-metamorphic evolution of the Alboran Domain of the western Mediterranean. Journal of Metamorphic Geology, 39(5), 591-615.
29. Mourabit, Z., Tabit, Garrido, C.J., Bodinier, J.-L., 2017. L'étude géochronologique de l'unité Filali (Rif interne, Maroc): implication pour U-Th-Pb de Zircon, Monazite et Rutile dans les métapelites, les gneiss et les migmatites.
30. Plumelle, C., Fouché, O., Cui, Y., Fabre, D., & Tabbagh, A. 2017. Théorie et pratique de la géotechnique-Tome 1-Outils pour la conception des ouvrages.
31. Sassioui, S., Aarab, A., Darbali, M., Ouchbani, A., Lakhloufi, A., El Hilali, M., & Larabi, A. 2022. Contribution to the Mineralogical Study Using Electrical Tomography in Foum Tizza Area, Eastern Anti-Atlas, Morocco. The Iraqi Geological Journal, 1-13.
32. Taj, B., Mastere, M., el Fellah, B., & Benzougagh, B et al. 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, 2023, n° 45, 45–59
33. Vernant, P., Fadil, A., Mourabit, T., Ouazar, D., Koulali, A., Davila, J.M., ... & Reilinger, R. 2010. Geodetic constraints on active tectonics of the Western Mediterranean: Implications for the kinematics and dynamics of the Nubia-Eurasia plate boundary zone. Journal of Geodynamics, 49(3-4), 123-129. https://doi.org/10.1016/J.JOG.2009.10.007
34. Zhdanov M. & Portniaguine O. 1999. Focusing geophysical inversion images. Geophysics, 64(3), 874–887.
35. Zhou, B. 2019. Electrical resistivity tomography: a subsurface-imaging technique. Applied geophysics with case studies on environmental, exploration and engineering geophysics.