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Impact of lithology and topography on the mechanical performance and environmental sustainability of Jorf Lasfar soils

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ABSTRACT

This study focuses on the geomechanical characterization of soils at the Jorf Lasfar site, located near El Jadida city in Morocco, within a context marked by natural rock formation processes. The main objective is to identify the nature of the soils in order to optimize the choice of construction techniques suited to local conditions. Our investigations reveal significant variability in the mineralogical and physical properties of the soils depending on altitude. Results show that higher-altitude areas are dominated by clayey limestone soils, characterized by specific plastic and mechanical behavior. Intermediate zones exhibit lithological diversity, including sandy-clay, marl-limestone, and tufa-limestone formations, while low-lying areas are mainly composed of sandy soils with distinct geomechanical properties. This variability is a key factor in defining construction methods adapted to each sector of the site.To support this analysis, several tests were conducted, including direct shear tests to assess mechanical strength, water retention curves to evaluate hydraulic properties, as well as laboratory and in situ tests. These tests enabled the establishment of correlations between the soils' physical properties, their structure, and their mineralogical and lithological composition. This integrated approach facilitates a better understanding of soil behavior under environmental and mechanical constraints.

Keywords: soil characterization, lithology impact, geomechanical properties, soil protection and reclamation, environmental monitoring.

INTRODUCTION

Traditionally, from the point of view of changes in physical state, cultivated soils are characterized by structural properties such as the structural stability and the cohesion. In particular, the soil cohesion has been assessed on the basis of Atterberg limits, geotechnical parameters used to determine the soil consistency. These limits vary according to a number of factors, including mineralogical nature, humidity and local climatic conditions. Studies dealing with different geographical regions have highlighted such variations. undefined-specifically, the tendency of a soil to densify under the effect of mechanical loads (Caron et al., 1996; Roger-Estrade et al., 2004; Yudina and Kuzyakov, 2023). This sensitivity highly depend on granulometric composition and clay content. The soil physical behavior is therefore an essential indicator of its suitability for cultivation. These analyses enable agricultural techniques to be adapted to reduce soil structure degradation. (Cardoso et al., 2013; Schoenholtz et al., 2000). The influence of clay and sand content on soil compaction mechanisms has been extensively studied, as these particle size fractions largely determine soil sensitivity to densification. At the same time, the role of the organic matter and limestone has been examined, as these elements play an essential role in aggregate cohesion and resistance to compaction (Murphy, 2015; Yang et al., 2023). The organic matter improves soil structure by increasing porosity, while limestone can strengthen or weaken this structure depending on its shape and distribution (Li et al., 2018). Analyzing the physical behavior of soils is therefore essential for assessing their agricultural potential. It enables one to predict how they will react to the mechanical pressures associated with farming activities or extreme climatic events (El Behairy et al., 2022; Al-Khreisat et al., 2025; Pal et al., 2020; Fischer et al., 2001). This study identifies the fundamental parameters such as soil texture, porosity, permeability and structural stability. It is an essential step in adjusting farming practices to specific soil conditions. It has been considered that the soil analysis is also part of a sustainable development approach, contributing to the efficient, long-term management of agricultural land (Shah and Wu, 2019; Keesstra et al., 2018).

The importance of understanding the interactions between the physical characteristics of soils, such as texture and porosity, and their mechanical behavior, particularly shear strength, is crucial for assessing soil stability and susceptibility to erosion, particularly in areas subject to climatic variations and intensive anthropogenic activities.

The Ljorf Sfar region, located south of El Jadida on Morocco's Atlantic coast, presents a number of major geotechnical challenges affecting the stability and the durability of construction projects. These problems are linked to the geological and geomechanically nature of the outcropping formations, as well as to local hydroclimatic conditions. From a geological point of view, the ground is essentially made up of loose or semi-consolidated sedimentary formations such as marl, clay, sand and weathered limestone (Wei et al., 2022). These materials often have low load-bearing capacity and high compressibility, and may be subject to differential ground movements under permanent or cyclic loads. The frequent presence of marly or clayey levels, particularly sensitive to variations in water content, creates significant risks of swelling or shrinkage, causing uneven settlement or cracking in built structures. The region is known for its rich, diverse and complicated geology, reflecting a long history of geodynamic activity. Marine transgressions and regressions occurred on numerous occasions in the second to quaternary geological sedimentary region that constitutes the Moroccan coastal Atlantic basin. The stratigraphy is dominated by well-developed sedimentary formations formed at different periods, notably in the Jurassic and Cretaceous. These formations are mainly limestone, marl, sandstone and sometimes conglomerate. In addition, the proximity of the coastline exposes certain areas to progressive marine erosion and rising water levels, aggravated by marine infiltration or heavy rainfall. This encourages soil dissolution, decompression and even slope instability.

In addition, the intense industrial activity in the Jorf Lasfar area – particularly around the port and chemical complex – involves large-scale works requiring deep foundations and appropriate, often costly, soil treatments. Geotechnical studies must therefore be systematic and in-depth to guarantee long-term stability, taking into account the site's mechanical, hydrogeological and environmental parameters (Laghzali et al., 2022;, Chaminé et al., 2018). The aim of this work is to contribute to these activities by approaching the geomechanically characteristics of the soils at Jorf Elsfar, near el Jadida city in Morocco, in order to identify their nature and optimizing the choice of construction techniques.

MATERIALS AND METHODS

Geological background

The study area is located in the Moroccan coastal Sahel, between the towns of Casablanca and Safi. It forms an endorheic coastal basin approximately 150 km long and 20 to 30 km wide. The region is characterized by consolidated dunes, arranged in long ridges oriented southwest to northeast, parallel to the Atlantic coastline. Due to its morphology and the geographical position, the area functions as a natural barrier, preventing the direct flow of surface water from the Abda-Doukkala plain and the Rehamna Massif toward the ocean. From a geological perspective, the Doukkala region is dominated by Cretaceous formations that constitute the nearly continuous substratum of the Plio-Quaternary aquiferous layers. Certain limestone levels within these formations contain the most important groundwater tables of the Sahel (de Barros et al., 2012; Jamaa et al., 2020).

At the end of the Neocomian, a marine retreat occurred, resulting in the absence of Lower Cretaceous formations. It was not until the Cenomanian that a new marine transgression took place, as evidenced by outcrops observed in the northeast of the Sahel. Boreholes drilled at Sidi Bennour in particular have revealed gypsum-rich marl-limestone levels attributed to this period. The thickness of these deposits is estimated at between 100 and 200 meters, indicating moderate subsidence in the region.

Eocene formations, rich in phosphates, outcrop only on the eastern edge of the Rehamna massif. Miocene deposits, likely present southeast of El Jadida and near Harichate, are made up of sandy marls and red clays. During the Plio-Quaternary, a marine transgression deposited yellow detrital limestone composed of shell debris and sand. Coastal dunes later formed from similar materials after the sea retreated. This period saw alternating transgressive and regressive phases, producing diverse lithological facies. These include conglomerates, porous shell-rich limestones, loose sands, hard recrystallized limestones, fine clay-rich dune limestones, and sandy marls.

The spatial distribution (horizontal and vertical) of these different facies is irregular and heterogeneous, typical of sedimentation in shallow marine environments subject to changing environmental conditions. Drilling data indicate a regular thickness of the marine deposits in the Abda-Doukkala plain (20 to 40 m), while in the Sahel region, these deposits are thinner (around 10 m). However, dunes can be up to 70 m thick above this marine bedrock (Figure 1).

The geological data collected also helped in selecting the most appropriate measurement instruments for the study context and in accurately positioning the data acquisition profiles (Li et al., 2018). During the field visit, several outcrops were observed near the study area, offering valuable insights into the structure and the composition of the different geological facies. These observations made it possible to construct the stratigraphic logs presented in Figure 2.

Soil erosion is a significant environmental challenge, especially in areas facing increasing natural and human pressures. It results from the combined effects of climatic factors (such as heavy rainfall and strong winds), topography (steep slopes), geology (loose or weakly cohesive soils), and the human activities like deforestation, overgrazing, poor farming practices, and unplanned urbanization. This process causes severe degradation of topsoil, leading to loss of fertility, reduced crop yields, sedimentation of water bodies, heightened flood risks, and instability of infrastructure.

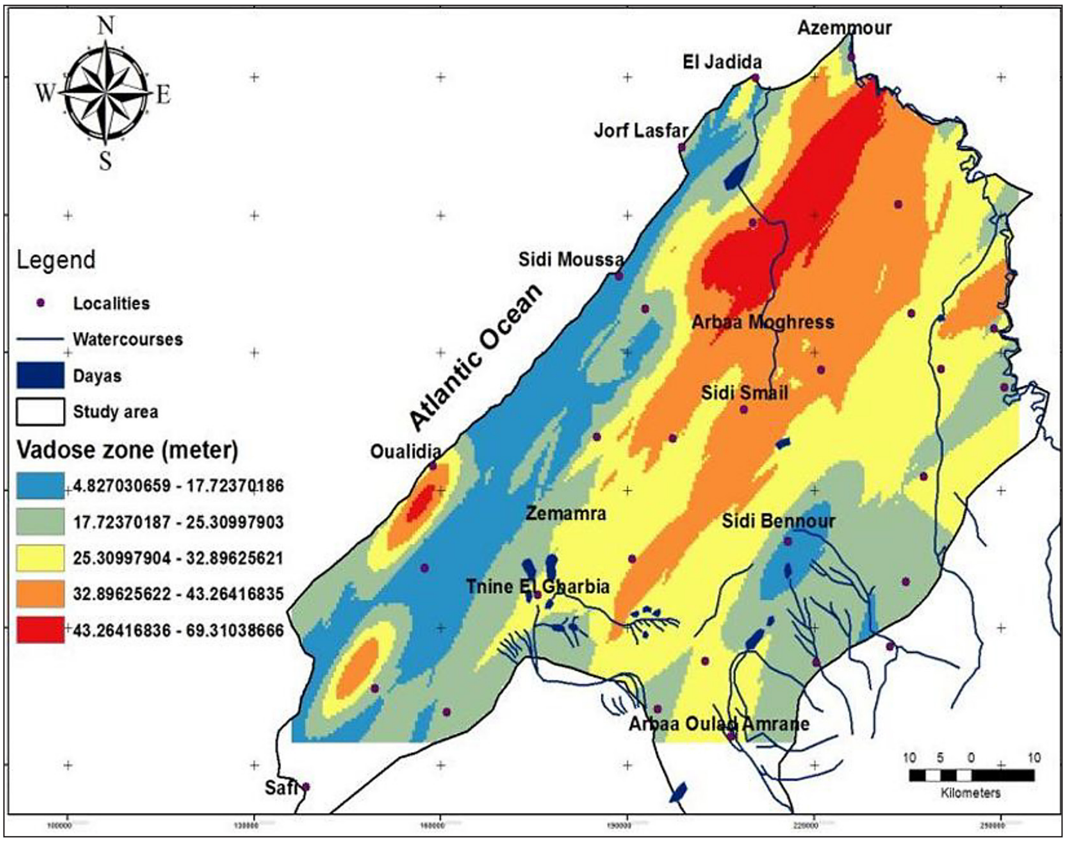

Figure 1. Representative map of unsaturated area (December 2024)

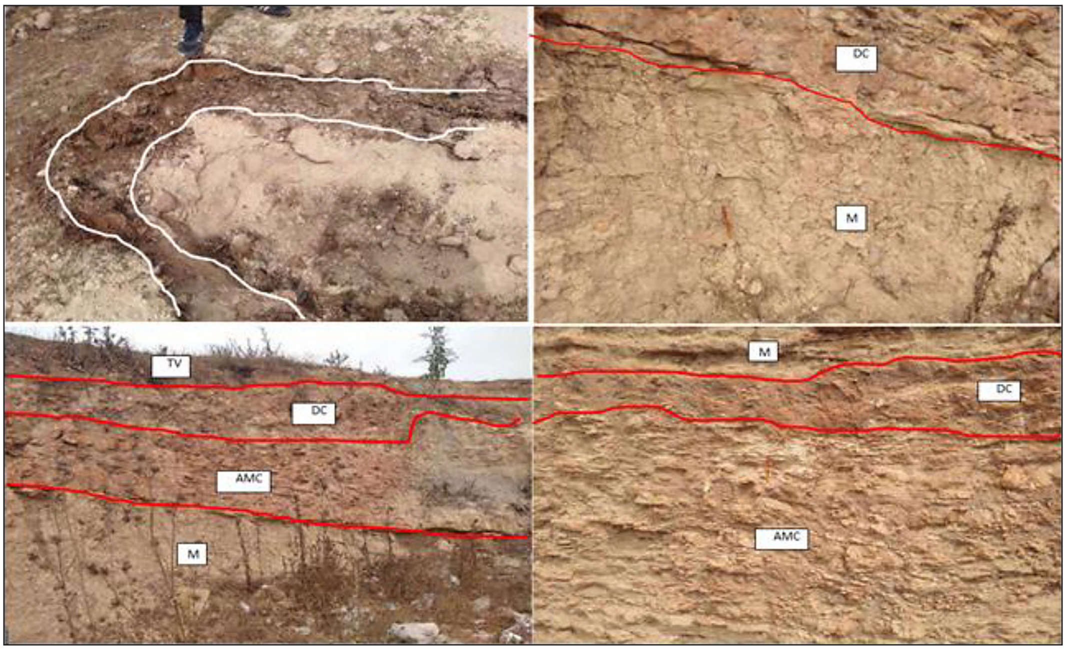

Figure 2. Jorf Lasfar – El Jadida cross-section. TV – topsoil; DC – limestone slab; AMC – Marl-limestone alternation Jorf Lasfar

In coastal and semi-arid regions like Jorf Lasfar – El Jadida, erosion is further worsened by marine influences and the loss of natural vegetation cover, highlighting the urgent need for soil conservation, reforestation, and sustainable land management. Current research in Jorf Lasfar focuses on understanding and mitigating geotechnical problems linked to erosion, particularly water erosion. Geological studies in El Jadida show that the gullied areas often have highly porous soils with shallow water tables. These conditions promote physico-chemical changes in unsaturated soils due to water flow, which intensify after gully formation, increasing ground instability and threatening surface infrastructure. Therefore, incorporating these geotechnical factors is crucial for effective land-use planning and infrastructure protection in the region (Khatibi et al., 2024; Soltaninejad et al., 2025; Parmar, 2024).

Methodology adopted

A geotechnical reconnaissance campaign was carried out as part of this study, in order to characterize the associated physico-mechanical properties of the soils. The approach involved several complementary stages (Flanclin et al., 2024; Aboubakar et al., 2025). Firstly, a preliminary analysis of the topographical and cartographic data enabled us to plan a rational layout of the sounding points. As a result, core holes and open pits whave been drilled uniformly across the entire perimeter, at depths ranging from 5 to 10 metres, depending on the specific needs of the project.

The core holes enabled us to take intact samples, while documenting the lithological features encountered. Mechanical shafts facilitated direct observation of soil structures and stratigraphic transitions. All the collected samples have been carefully packaged and sent to a certified geotechnical laboratory for standard tests including particle size analysis, Atterberg limits, the natural water content, normal and modified Proctor tests, and bearing capacity.

These tests enabled us to accurately assess the consistency of the materials, their degree of saturation, their compactness, as well as their mechanical behavior under load. A total of 27 core holes were drilled in accordance with the planned layout, covering the entire site in a homogeneous manner. The results of these boreholes were interpreted to establish typical geotechnical profiles, locate the depth of the water table where present, and identify any geotechnical constraints such as unstable soils, areas prone to shrink-swell, or insufficiently load-bearing layers. All the obtained data was used to formulate technical recommendations adapted to local conditions, with a view to ensuring the stability and durability of the structures to be installed. (CBR), compressibility, and other specific tests depending on the nature of the soil (Figure 3).

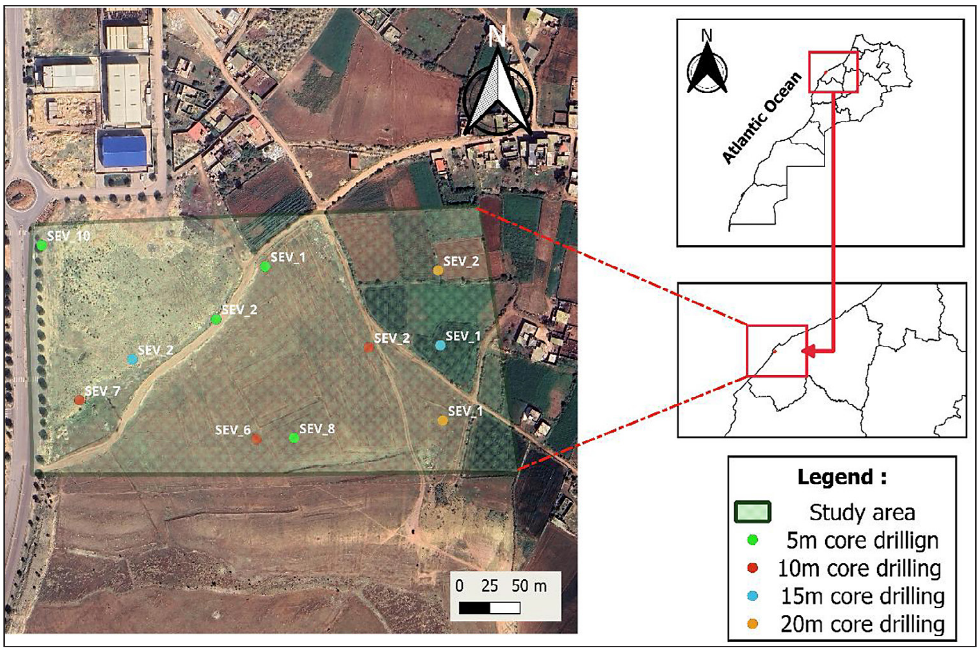

Figure 3. Map of core sampling sites

Processing techniques

In this geotechnical investigation, data were acquired mainly by vertical electrical sounding (VES) to characterize the nature and resistivity of the subsoil layers. Measurements were taken with a Schlumberger device, guaranteeing good vertical resolution, according to a standardized protocol. Raw data were processed with IPI2Win software to model the underground structure and detect geoelectric discontinuities. The used equipment included a geo-resistivity meter, metal electrodes, cables, a hammer for electrical contact and a GPS for precise borehole location (Banton et al., 1997). This method makes it possible to measure apparent resistivity at different depths by increasing electrode spacing, providing a reliable basis for assessing the physical and mechanical properties of the studied soils (Samouëlian et al., 2005, Dafalla and AlFouzan, 2012).

RESULTS FROM THE STUDY SITE

The results were obtained from the electrical sounding measurements carried out in the study area. These results compared with geotechnical data, geological observations and field observations to gain a better understanding of soil behaviors and erodibility. At the study site, the electrical soundings were taken at various depths, ranging from 5 to 20 meters, to analyze the apparent resistivity of the soil.

Soil lithology at core drilling depths of between 5 and 20 m

Soil lithology at 5 m core drilling depths: 11 electrical boreholes drilled to a depth of 5 m, and the formations encountered are shown on Figure 4.

Soil lithology at the 10 m deep core holes: 7 electrical holes drilled to a depth of 10m , and the formations encountered are shown in Figure 5.

Based on boreholes drilled down to a depth of 20 m from their initial positions, the soil in place shows the following lithological succession (Figure 6):
- topsoil cover.
- succession of alternating layers of calcareous tuff/ marl-limestone tuff with coarse elements and a sandy-clay matrix;
- marly limestone with a roof varying from 6.50–7.50 m/ TN depth.
- beyond this, the presence of a sandstone passage at the level of SC20-2 at 13.00 m/TN.

Results of electrical sounding

The graphical representations in terms of real curves obtained from vertical electrical soundings (VES) were interpreted using specialized geoelectric modeling software (Akiang et al., 2024; Niculescu and Andrei, 2019) (Figures 7–10).

Figure 4. Lithology of soils in the area of the 5 m deep core holes

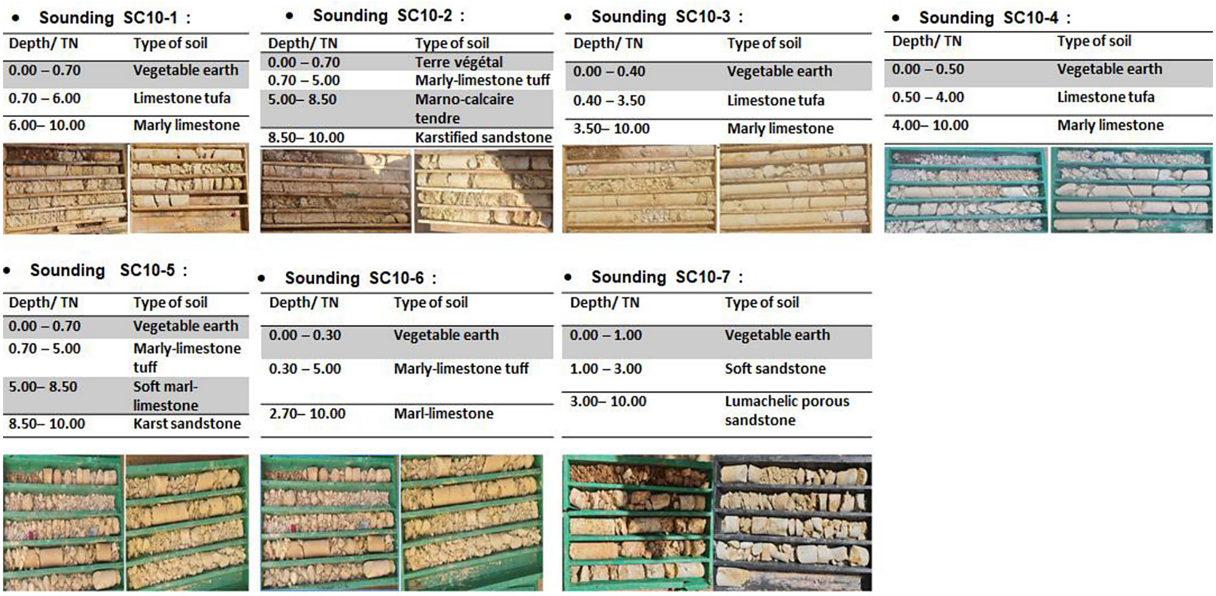

Figure 5. Soil lithology at 10 m deep core hole

This method allows for the identification of different subsurface layers based on their apparent resistivities and respective thicknesses. Each borehole profile reveals a succession of geoelectric layers, reflecting the lithological diversity and the complexity of the study site (Aliou et al., 2022). Detailed analysis of these data helps to better understand the distribution of materials and their physical properties. This understanding is essential for assessing soil stability and predicting its mechanical behavior. Consequently, this approach provides valuable information for planning geotechnical works and land development. It also enables the identification of the potential weak or the heterogeneous zones within the subsurface (Marache et al., 2009; Dodagoudar, 2018).

Electrical sounding curves at 20 m depth

Analysis and interpretation of the results obtained at different depths enable us to distinguish the vertical structuring of the soils and

- **Sounding SC20-1 :**

Depth/ TN	Type of soil
0.00 – 1.00	Vegetable earth
1.00 – 7.50	Alternating limestone tuff / marl-limestone
7.50– 20.00	Marno-limestone

- **Sounding SC20-2 :**

Depth/ TN	Type of soil
0.00 – 0.70	Vegetable earth
0.70 – 3.50	Limestone tuff
3.50– 6.50	Marno-limestone tuff
6.50 - 13.00	Marno-limestone
13.00 - 20.00	Sandstone

Figure 6. Lithology of soils in the area of the 20 m deep core holes

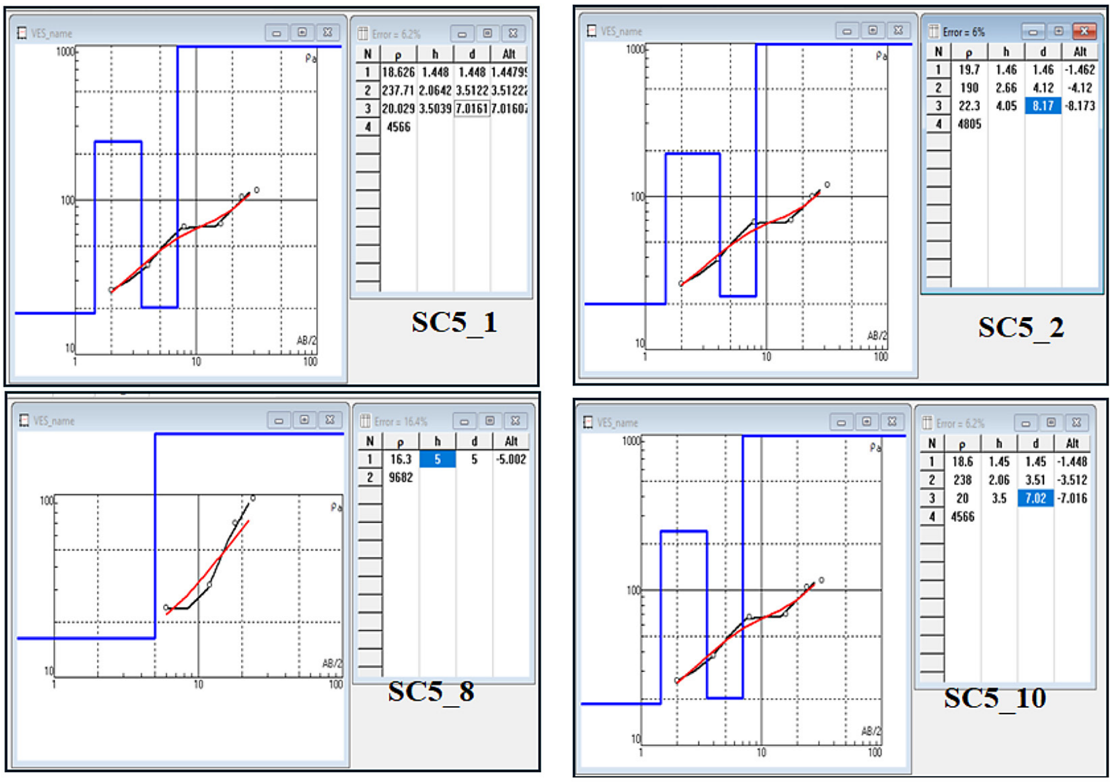

Figure 7. Curves from a 5 m-Deep electrical borehole

characterize the layers encountered within the studied subsoil. At a depth of 5 m, most electrical boreholes reveal two to three layers, with a succession of materials ranging from loose soils (fill), followed by semi-soft rock formations (calcareous tuffs and calcareous marl), to more compact sandstone levels, indicating a gradual increase in compactness and strength with depth.

The structure at 10 m generally comprises three to four layers, with a gradual transition to soft rock formations (marl-limestone), followed by a very hard, more resistant level (sandstone). Boreholes at 15 and 20 meters reveal three to five well-differentiated horizons, including semi-firm to semi-hard deposits (calcareous tuffs / marl-lxzimestone), followed by a more resistant bedrock (sandstone / karstified sandstone).

Results of pressuremeter tests

The pressuremeter tests were carried out to assess the mechanical characteristics of the

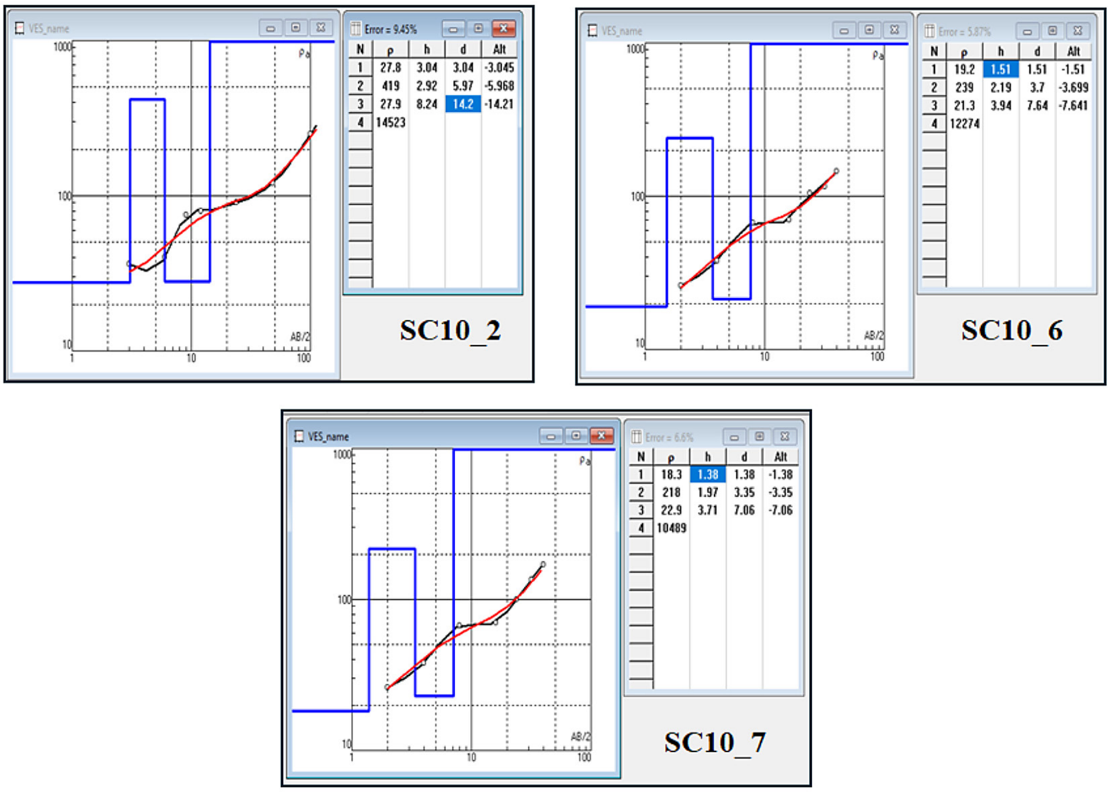

Figure 8. Electrical sounding curves at 10 m depth

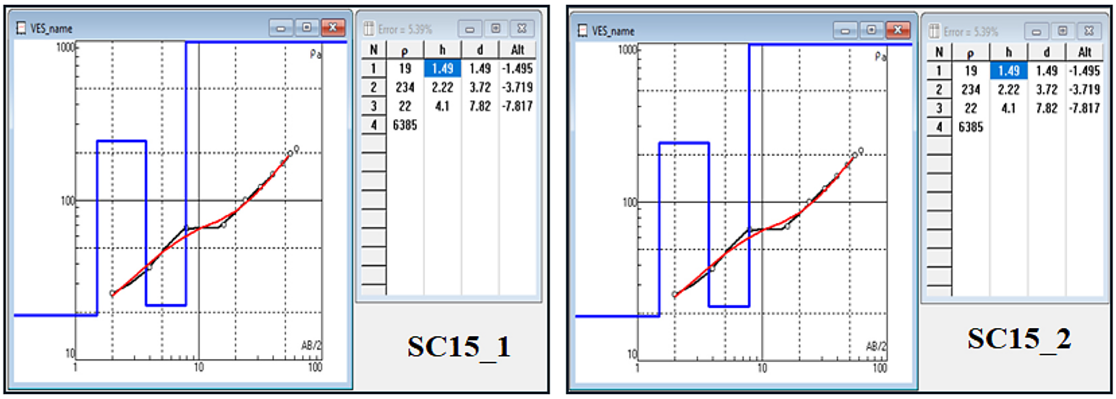

Figure 9. Electrical sounding curves at 15 m depth

formations encountered. The pressuremeter testing was only carried out on the 20 m electrical borehole in order to mechanically characterize the deeper layers, where stresses are greatest. This choice optimized resources while providing representative data for geotechnical analysis of the site. Table 1 summarizes the results of the pessuremeter tests carried out at depth 20 m: These results confirm the compact nature of these marl-limestones. The least consistent passages, corresponding to the marl joints (sandy marl), have a low limit pressure of between 1.8 and 2.1 MPa.

LABORATORY TEST RESULTS

Soil identification tests

The representative samples of the different soil types encountered on the site were collected and subjected to a series of laboratory tests to characterize their physical and chemical properties. Among these analyses, a particle size distribution study was carried out in accordance with the NF EN ISO 17892-4 standard, allowing the determination of particle size distribution and soil texture.

Table 1. Pressuremeter tests carried out at a depth of 20 m

Depth	Pf	Pl	EM
(m)	(MPa)	(MPa)	(MPa)
4.50	2.5063	4.26	179
6.50	2.3529	4.00	178
8.00	3.0500	> 5	222
9.50	2.4914	4.24	178
11.00	3.2034	5.45	229
12.50	1.7765	3.02	171
14.00	2.4176	4.11	179
15.50	1.0647	1.81	99
17.50	1.3529	2.30	114
18.50	2.9529	5.02	201

Depth	Pf	Pl	EM
(m)	(MPa)	(MPa)	(MPa)
4.50	1.6061	2.73	115
6.50	2.0588	3.50	127
8.00	2.8235	4.8	145
9.50	1.3840	2.35	99
11.00	1.2598	2.14	90
12.50	1.5317	2.60	109
14.00	1.0588	1.80	84
17.50	1.1764	2.00	96
18.50	2.4705	4.20	140

Additionally, the Atterberg limits were measured according to standards NF P94-052-1 and NF P94-051 to assess the plasticity and consistency of clayey soils, which are essential parameters for understanding their mechanical behavior. Finally, the methylene blue value was determined through a spot test following the NF P94-068 standard, enabling estimation of the clay content and cation exchange capacity of the soil. These tests provide a solid foundation for interpreting soil characteristics and anticipating their response to mechanical and environmental stresses. The granulometric analysis results obtained on samples taken from the boreholes are summarized in Table 2.

Mechanical test on soil

The marl-limestone tuff formation has been subjected to a series of mechanical laboratory tests, including direct shear box tests and odometer tests to assess its compressibility. The results of these investigations are summarized in Table 3. This could enable us to better characterize the mechanical behavior of this geological formation.

The results show that the marl-limestone tuff present on the site has a low plasticity index, leading to a soil with low compressibility. This characteristic indicates a good resistance with respect to the deformation under moderate loads. Furthermore, the measured preconsolidation stress is approximately 1.8 bar, reflecting the maximum pressure the soil previously endured before any additional deformation. Finally, the swelling index is very low, around 0.02, indicating that the soil has a minimal tendency to expand when exposed to moisture. These parameters confirm the relative stability of this material against the mechanical and the moisture-related variations

Rock identification test

The mechanical behavior of the site rocks was assessed in the laboratory on the basis of representative samples, using the following tests:

- Simple compression test in accordance with standard NF P94-420.0.
- Measurement of the dry density of a rock element by hydrostatic weighing in accordance with standard NF P94-064.

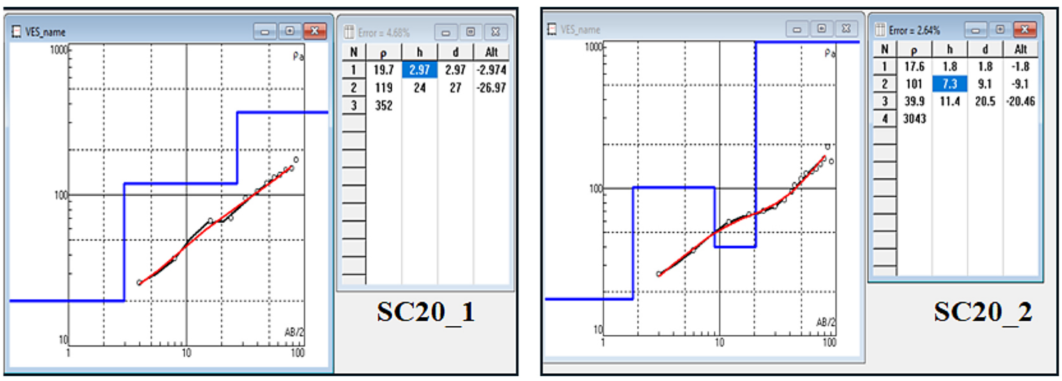

Figure 10. Electrical sounding curves at 20 m depth

Table 2. Granulometric analyses performed on samples collected from boreholes

Withdrawal/TN	Ø < 0.08 m	m Ø < 2 mm	Ø < 20 mm	W_L%	I_P%	???	LCPC	GMTR
PP6 (1.30 m)	45	61	79	37	14	0.98	SA	A2
PP7 (1.50 m)	38.0	57	87	34	11	0.81	SA	A1
PP8 (1.30 m)	38	81	70	34	11	0.64	SA	A1
PP10 (1.80 m)	21	36	56	24	8	0.36	Sl	B5
S3 (0.70 m)	35	59	85	33	10	0.62	SA	B5
S6 (0.70 m)	35	59	85	29	9	0.62	SA	B5
S7 (0.70 m)	35	59	85	33	10	0.64	SA	B5
S8 (0.70 m)	89	99	100	45	13	0.9	Lp	A2
S9 (1.40 m)	50	78	96	35	12	0.67	SA	A1
SC5-1 (1.00–2.00 m)	58	82	100	26	5	0.97	Lp	A1
SC5-4 (1.50–3.00 m)	50	71	89	27	8	0.93	SA	A1
SC5-11 (3.50 m)	45	73	93	28	6	0.93	SA	A1
SC10-1 (4.00 m)	75	87	100	27	6	0.87	Lp	A1
SC10-2 (7.50 m)	77	81	88	33	7	0.95	Lp	A1
SC15-1 (7.00 m)	89	99	100	36	12	0.79	Lp	A1
SC20-2 (5.00 m)	74	86	100	29	6	0.87	Lp	A1

Table 3. Mechanical tests of rectilinear shearing on the box and odometric compressibility

Sampling location	C'p (kPa)	Φ (°)	Compression index	Swelling index	Pre-consolidation pressure (kPa)
SC20-1	18	26	0.16	0.02	200
SC10-3	17	23	0.14	0.02	160

Table 4 summarizes the obtained results showing a precise quantification of the mechanical characteristics of the rocks in the field.

The obtained finding show that the marl-limestone samples have low to very low compressive strengths, reflecting the relative fragility of this material. Despite this low mechanical strength, the density of the samples remains high, at around 2.2 g/cm³, a typical feature of marl-limestone rocks. Due to their brittleness, unconfined compressive strength (Rc) testing is difficult, if not impossible, for most samples, as they fracture during cutting operations. This limitation highlights the need for alternative methods or special precautions to assess the mechanical behavior of these brittle rocks. These observations are essential for a better understanding of the stresses to which soil can be subjected in the field.

Retained geotechnical model

All results from in situ tests and geotechnical surveys conducted on the site have been carefully compiled and summarized in Table 5, presented on the reverse side. Based on these data, a geotechnical model representative of the actual soil conditions was developed. This model allows for a precise description of the sequence of different geological layers and their mechanical properties. It serves as a crucial tool for assessing the soil's behavior under various stresses. This approach supports the informed decision-making for engineering works and site development.

The relevant parameters used for the calculations correspond to the conservative characteristic values, needed to guarantee the safety and reliability of the analyses. These values were chosen taking into account the significant lateral variability of the geological facies observed on the site. The terrain studied consists mainly of rocky limestone marl with low mechanical strength. These marls are interspersed with alternating layers of more resistant, compact sandy marls. This lithological complexity has a direct influence on the overall behavior of the soil under stress. As a result, all parameters incorporate these variations to best reflect actual subsoil conditions.

Table 4. Mechanical behaviour of the rock in the field was quantified in the laboratory on representative samples

Nature lithological	Sampling location	Density (g/cm^3)	RC (mPa)
Marl-limestone/limestone	PP2 (1.80 m/TN)	2.34	7.08
	SC5-5 (4.00 m/TN)	2.41	10.51
	SC5-9 (4.50 m/TN)	2.35	9.53
	SC5-10 (3.40 m/TN)	2.43	***
	SC10-1 (6.00 m/TN)	2.15	6.85
	SC10-1(7.00 m/TN)	2.19	5.9
	SC10-6 (2.00 m/TN)	1.95	***
	SC10-6 (6.50 m/TN)	1.96	***
	SC15-1 (12.0 m/TN)	2.51	8.54
	SC20-1 (4.00 m/TN)	2.11	9.98
	SC20-2 (11.00 m/TN)	2.16	***
Karstified sandstone	SC10-2 (9.00 m/TN)	2.32	***
	SC10-7 (2.00 m/TN)	2.21	***
	SC10-7 (5.00 m/TN)	2.28	***
	SC10-7 (9.00 m/TN)	2.30	***
	SC20-2 (20.00 m/TN)	2.72	***

Table 5. Various in situ tests and surveys carried out on the site

Designation	Depth (m)	Density (g/cm^3)	Rc	Pl (MPa)	Em (MPa)
Topsoil	0.00–1.00	–	–	–	–
Calcareous tuff	1.00–7.50	1.7	–	1.8	80
Alternating calcareous tuff/marno- tuff	7.50–20	1.95	5.9	3.1	120

Classification of the site's seismic zone

In accordance with the French Seismic Building Regulations (RPS, 2011), the site's seismic zoning, expressed in terms of acceleration and velocity of seismic motion, is shown in the diagrams below. These zonings enable us to characterize the local seismic hazard with a view to incorporating it into the design of structures (Figure 11a and 11b).

Certain geophysical and geotechnical investigations carried out at the Jorf Lasfar site have revealed a pronounced vertical stratification of the subsurface, marked by alternating layers of limestone, marl, and clay, as summarized in Table 6. This complex geological arrangement poses considerable challenges for foundation design and construction. In particular, the presence of marly joints and the ongoing dissolution of limestone contribute to the development of karstic features. Karstification occurs when slightly acidic water dissolves calcium carbonate within the limestone, resulting in the formation of underground cavities and voids. These karstic structures create zones of weakness that can significantly compromise the stability and load-bearing capacity of foundations. Consequently, detailed site investigations and careful geotechnical modeling are essential to identify and mitigate these risks. Understanding the extent and distribution of karstification is crucial to ensure the long-term safety and durability of any engineering works in the study area.

An integrated approach combining geophysical and geotechnical investigations is essential to assess these complex conditions. The vertical electrical soundings (VES), also known as Schlumberger Electrical Soundings, offer an effective method to determine the electrical resistivity of the subsurface at depth. This technique can be used not only to map subsurface heterogeneities but also to identify areas of low resistivity associated with marl formations and locate karstic structures. The data obtained by SEV is supplemented by the pressuremeter and odometer tests, which provide direct information on soil mechanical properties such as shear strength and compressibility. The integration of these results enables geophysical detected anomalies to be validated

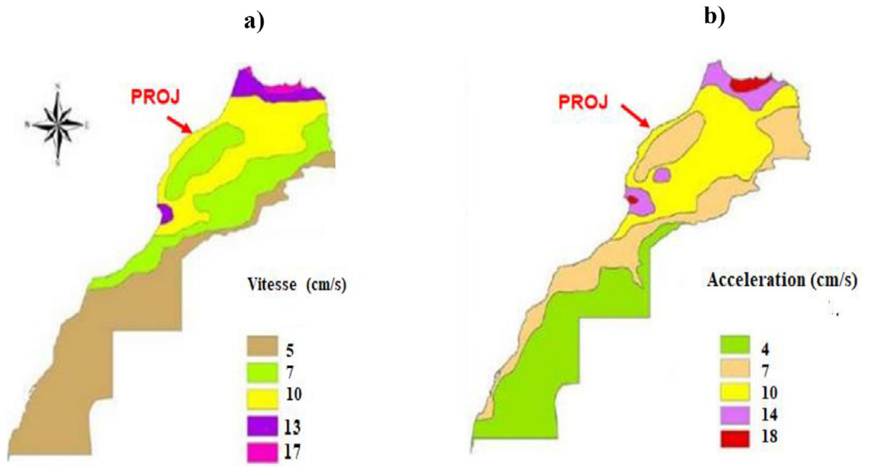

Figure 11. (a) Seismic speed zoning map – 10% probability of occurrence in 50 years (RPS Maroc 2011, speed in cm/s), (b) seismic zoning map for acceleration – 10% probability of occurrence in 50 years (RPS Maroc 2011, velocity in cm/s)

Table 6. Typology of sites and associated seismic coefficients according to soil type and depth

Sites	Nature	Coefficient
S1	All-depth rock Strong soil depth < 15 m	1
S2	Strong soil depth > 15 m Medium-firm soil depth < 15 m Loose soil depth < 10 m	1.2
S3	Medium-firm soil depth > 15 m Loose soil depth > 10 m	???

and geotechnical models to be refined. This could provide a better understanding of the soil behaviors. This comprehensive approach is crucial for the design of foundations adapted to specific the site conditions, such as the use of bored or driven piles, and for the implementation of drainage and corrosion protection measures to preserve the integrity of structures in a potentially aggressive marine environment.

CONCLUSIONS

The comprehensive testing conducted on the soils and rock formations at the site has enabled a detailed characterization of their physical and mechanical properties. Granulometric analyses combined with Atterberg limits revealed significant variability in soil textures and plasticity, reflecting the complex lithological nature of the terrain. Mechanical tests indicated low compressibility and moderate strength, particularly within the marl-limestone formations prevalent across the site. The identification of karstification and lithological heterogeneity further emphasizes the necessity for detailed geotechnical modeling to ensure the structural stability of future developments.

By integrating results from both in situ and laboratory testing, a representative subsurface model was developed, capturing the spatial variability of soil properties influenced by topography and lithology. This model forms a critical foundation for the accurate design of building foundations and other geotechnical structures. Furthermore, incorporating local seismic parameters into the analysis strengthens the design approach, providing resilience against regional natural hazards and ensuring the safety of infrastructure.

Overall, this study provides a robust scientific basis for the planning, sizing, and execution of engineering works on this geologically complex site. It highlights the value of multidisciplinary investigations in achieving sustainable and safe land development while minimizing environmental impact. The methodologies and findings presented herein may serve as a practical reference for similar projects situated on heterogeneous terrains, supporting soil protection and optimized land use.

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