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ORIGINAL PAPER

Geotechnical Characterization of the Marchica Lagoon Site (Nador, Northeastern Morocco) and Detection of Potential Problems

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Abstract In this paper, a geotechnical characterization of the superficial formations surrounding the Marchica lagoon (Nador, NE of Morocco) is presented. Five zones that have similar geotechnical characteristics are identified, and for each zone, a geotechnical model has been built from the results of in situ and laboratory geotechnical tests. The barrier zone is the only zone with an abundance of sand that can reach major depths (> 30 m), the Bou-Areg and Arekman zone is constituted by silty clays that can reach 30 m. The Atalayoun zone is geotechnically, the unfavorable zone, the plasticity of the clay deposit, which can reach a thickness of 8.5 m, is relatively high, and with a density of 990 kg/m^3. This type of soil can create serious geotechnical problems. The latter zone is an area with an abundance of volcanic rock. Based on geotechnical characterization and modeling, a geotechnical database has been created to build thematic maps using GIS software to facilitate the interpretation of results. Several geotechnical problems have been detected through conventional and non-conventional methods in the different delimited zones, such as the low bearing capacity of the soil, settlement, and liquefaction. These results constitute an essential tool for preliminary geotechnical studies in this area. In addition, the model obtained in this work will be helpful for the optimization of geotechnical investigation campaigns. Therefore, this paper will be useful for the facilitation of decision-making by the authorities responsible for the development and urban planning in this area. Furthermore, the final product of this study can also be used as a methodological reference to approach the treatment of geotechnical problems in lagoons and coastal areas.

Keywords Geotechnical characterization · Bearing capacity · Settlement · Liquefaction · Coastal lagoons · Marchica (Nador, eastern Morocco)

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Introduction

When civil engineering projects are based on limited geological site data, geotechnical problems frequently arise and, consequently, the works suffer from cost increases and delays [1]. The different lithologic units must be characterized, located and defined through geotechnical investigations [2] to reduce these problems. The determination of soil properties, both geotechnical and geological is an important topic in engineering geology because of, for example, foundation stability problems [3]. Theses information helps to develop a conceptual geological model [4], which is beneficial for the specific site project or another project with similar conditions [1]. Different authors have tried to present the geological conditions and geotechnical characteristics of different zones using a synthetic model [1], [5–10].

Coastal lagoons are shallow aquatic ecosystems that are developed at the boundary between terrestrial and marine ecosystems [11]. These environments correspond to masses of marine waters located in a terrestrial domain. They are

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separated from the ocean by a barrier generally parallel to the coast, leaving one or more restricted openings that remain open at least intermittently [12]. Coastal lagoons are usually formed where the sea has submerged the valleys during the later stages of the late Quaternary marine transgression [13]. In general, lagoons are reasonably calm environments, when compared to seas and oceans, which allow active and continuous sedimentation over time. These sediments are often silts and clays carried by streams containing a significant amount of organic matter. The presence of the vegetation at depth in the lagoons and banks is also a factor, which favors sediment deposition.

It seems logical, when studying geotechnically the soil around the lagoon, to list the potential problems in this type of environment, which are, in general:

- Variation in the mechanical and/or granulometric properties of the surface layers due to the effects of floods, exceptional torrential flows or rough seas. These modifications may render the previously stable soil surface impassable.
- Abrupt variation in compressibility characteristics of the sediment could lead to an excessive differential response. The behavior can vary from very soft or soft soils to hard or dense soils over a relatively short distance.
- It is known that gypsum undergoes alternating hydration and dehydration in the hot and humid conditions that characterize some lagoon environments. When this mineral is abundant, associated volume changes can cause problems.
- The location of coastal lagoons means that most of them have an abundance of sand and a water table, which is very close to the surface, which makes the risk of liquefaction very high if the lagoon is in a seismically active zone.

In this work looking to answer several questions, can the lagoon area studied in this work have geological and geotechnical problems? If the answer is yes then what are these problems? Can we study all these problems? After answering these questions, what is the benefit of this work?

To answer these questions, a geological and geotechnical characterization of the area is essential to know the classification and properties of the soils, and then to understand the geotechnical problems that can be associated with each type of soil.

Study Area

Marchica is one of the largest lagoons in the south of the Mediterranean Sea (Fig. 1), it has an exceptional natural asset, linked to the richness and diversity of the ecosystem; hence, the Marchica lagoon has been identified as a site of Biological and Ecological Interest of great importance. To develop and promote this site, a major development projects was launched by the Marchica Lagoon Development Agency over a total area of 2000 ha, including seven projects: Atalayoun; Two seas site; the new Nador city; Flamingos bay; Sport city; Marchica orchards and; Fishermen village. The whole project will allow the creation of golf courses, a space dedicated to water and equestrian sports, hotel areas, residential areas and fishing and recreational harbors.

This Ecosystem lies parallel to the coast in the form of an oval basin. It is isolated from the Mediterranean Sea by a dune cord of 25 km long facing NW–SE. A new entrance was made by the agency for the development of the Marchica Lagoon site to ensure the good regeneration of lagoon water through communication with the Mediterranean, and to allow access to the lagoon of boats with drafts of up to 5.5 m.

The study area (Fig. 1) is the enlargement in 4 km of the perimeter of the Agency for the Development of the Marchica Lagoon scope.

The Marchica Lagoon, also known as the Bou Areg Sebkha, is the largest lagoon in Morocco with an area of 115 km^2; it is located in the northeast of Morocco on the Mediterranean coast, and precisely between Cape Three Forks and water Cape.

The plains of Bou Areg and Gareb have significant water reserves in the form of an aquifer; this aquifer, on the Bou Areg plain, has a surface area of 160 km^2, its water table is located near Kebdana at a depth of 60 m, and only 1 m from the shoreline, these waters would no longer flow into the lagoon very locally and it is increasingly confronted with problems of marine intrusion [14].

Geological, Sedimentological and Tectonic Setting of the Study Area

The Marchica lagoon is part of the Nador-Melilla basin which is one of the post-orogenic basins of the Northeast Rif [15]. This paralic basin was formed following polyphase tectonics which resulted in the Quaternary uprising toward the west, at Cape Three Forks, and subsidence on the Bou-Areg plain [16]. The Beni Bouifrour, Gourougou and Cape Three Forks massifs are part of the Rif Cordillera. As can be seen in Fig. 2, the basin of the Marchica Lagoon is characterized by four structural domains:

- The Gourougou volcanic massif: Located west of the lagoon, its volcanic activity began following the collision between the European and African continents [17]. Formed of potassium calc-alkaline lava related to

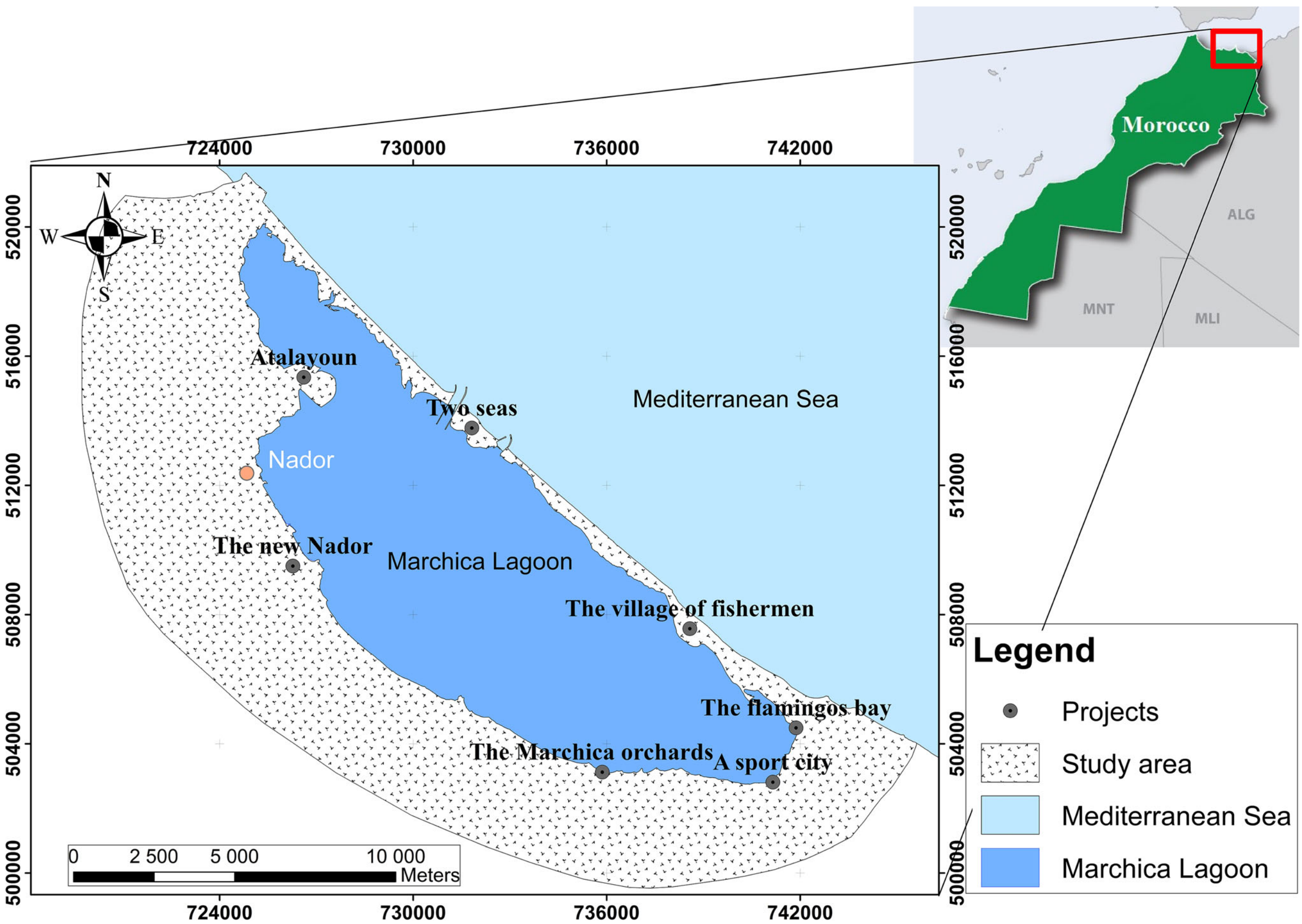

Fig. 1 Location of the Marchica lagoon and delimitation of the study area

Messinian rhyolitic volcanism and basic lava of the Plio-Quaternary age [18]. It is a stratovolcanic complex which is 887 m high; it is 25 km long and 15 km wide [19].

- The Beni-Bou-Ifrour massif: Located southwest of the lagoon, known in the past for the exploitation of iron ore. It is 699 m high and constitutes the base of Gourougou volcanism, its history extends from the Jurassic period (limestone, sandstone, and marl) to the Cretaceous period (schisto-sandstone and volcano-sedimentary series) [20]. It is composed of metamorphic rocks of Mesozoic age, intersected by granodiorite veins and affected by a NE–SW fault network [21].
- The Bou-Areg plain [22]: This plain falls under the "Gareb-Bou-Areg" subsidence Basin from the Neogene Age. Plio-Quaternary age deposits cover most of it, The Gareb-Bou-Areg basin appears to be the result of lithospheric flexure under load due to crustal thickening in the collision zone between the European and African continents.
- The Kebdana massif [23]: it is 937 m high and is constituted of a series going from the Jurassic to the Mio-Pliocene age. The Jurassic formations consist of marls and marl-limestones at the base, then sandstone and limestone sandstone, and limestone and dolomitic limestone at the top. The whole area is locally covered by Miocene age formations, mainly limestone and marl.

The formation of the Nador Lagoon is incorporated into the history of the Mediterranean coastal basin in northeastern Morocco. The geological evolution of this part of the northeastern Rif is characterized by the combined influence of tectonics and volcanism [24]. In the Jurassic-Cretaceous period, the Kebdana and Beni-Bou-Iffrour massifs formed first, then the whole area underwent a series of transgression-regression cycles, and tectonic displacements related to the main orogenic Rif movements [15, 25]. These movements resulted in the formation of the basins in the distension regions, as well as by folds in the compression zones that have lasted from the Tortonian period to today. These stages of deformation are accompanied by calc-alkaline volcanism (from 9 to 6.6 Myr), Shoshonitic (from 7 to 5.4 Myr) and alkaline volcanism (from 4.7 to 2.6 Myr) [17]. The succession of tectonic movements includes the first phase of synchronic extension to the

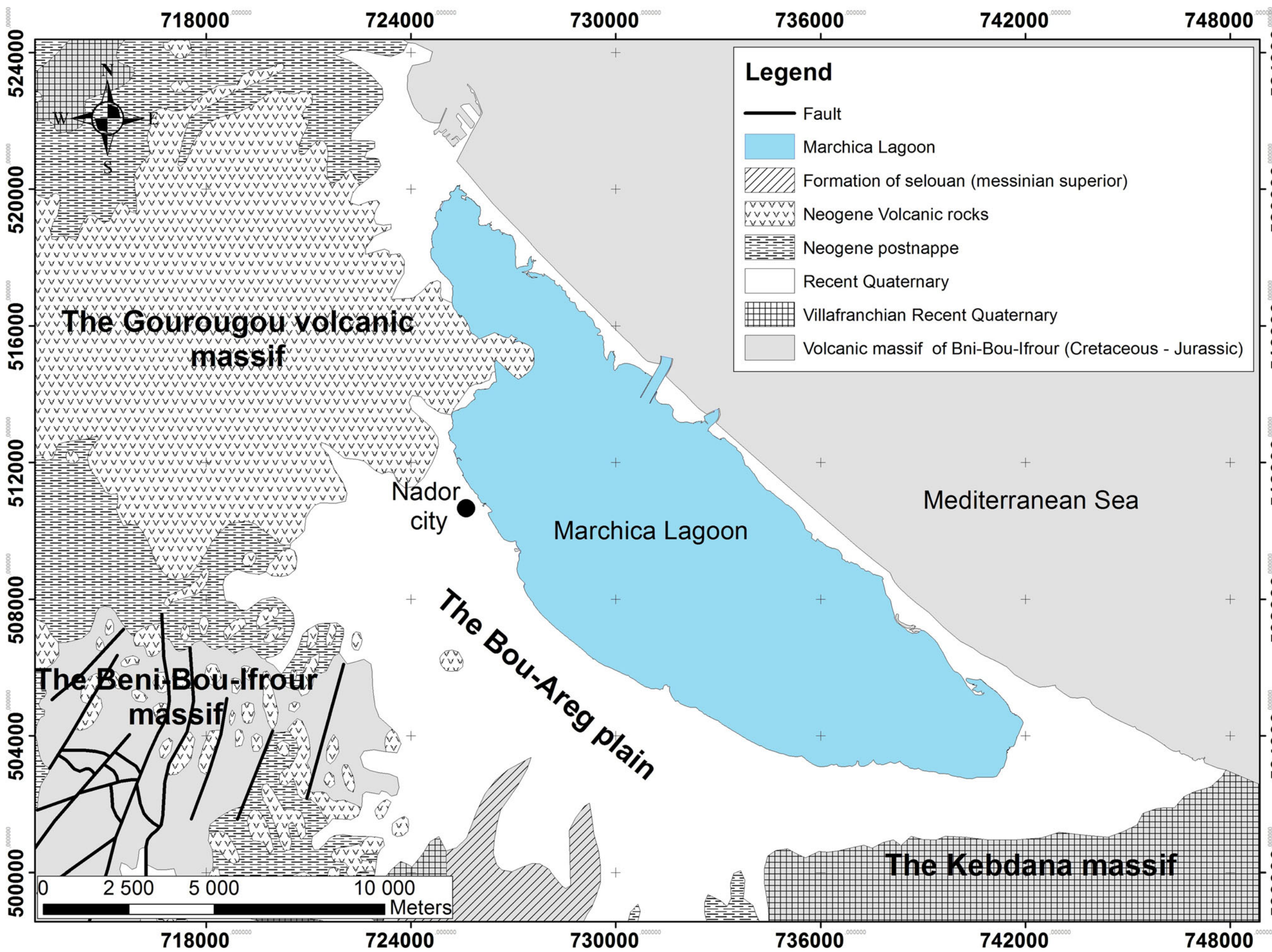

Fig. 2 Map of the main geological units of the study area and its surroundings

Tortonian period that contributed to the individualization of basins and the subsidence of the Bou-Areg plain through the normal fault movements [19]. The second phase of compression started from the old Quaternary period,which gives rise to a replay of some accidents which are manifested by significant seismic activity [19].

Generally, the Melilla Basin recorded three major sedimentary cycles: an Upper Tortonian cycle, a Messinian cycle, and a Pliocene cycle [15]. In the late Quaternary period, a lowering caused by the NW–SE fault movement at the end of the Pliocene period caused the subsidence of the Bou-Areg plain and the formation of the Marchica lagoon [15]. The barrier that would contribute to the isolation of the lagoon was formed in two stages [26]: An ante-Holocene stage that probably began in the Late Pleistocene period. In the past, this formation corresponded to subtidal bars of the channel at the mouth of the River Selouane; and a second Holocene stage, marked by the emergence of estuarine bars and the formation of a soil which is 3000 years old [27].

The Nador lagoon is framed by various facies formations, and the contributions of the sedimentary material are heterogeneous. The sedimentary materials are detrital dominant ones of local origin, which is shown by the mineralogy and the granularity of the deposits. They faithfully reflect the mineralogy of the watershed formations, marine inputs, plus biogenic and authigenic minerals (gypsum) formed in situ, as well as aerosols [20, 28–30].

The surface deposits show three facies: sandy, clay-silty and clay-silty-sandy. The processions of clay minerals are show few differences with a dominance of illites and, in descending order, kaolinites, chlorites, and smectites [29].

The superficial sediments have varying degrees of total organic carbon (TOC) and sulfur may be important (7.5 et 1.8% respectively). These high levels are mainly recorded in the center of the lagoon. The distribution of these is controlled by hydrodynamism and a degree of anthropization [31].

Raji et al. [32] studied the sedimentology of the Marchica lagoon Based on seismic data and integrated core, they recognized two main stages of marine sand filling separated by a period dominated by fine-grained sedimentation. The youngest sand unit was deposited between 1500 and 1900 CE, during the Little Ice Age.

Morocco is a country of moderate seismic activity, subdivided into many areas of homogeneous seismicity with approximately the same level of seismic risk for a given probability of occurrence (10% in 50 years).

The Marchica Lagoon is located near the Alboran Sea, which is a seismically active zone known for the propagation of transverse faults caused by the convergent dextral movement between the Eurasian and African plates, and which is in the order of 5 mm/year in a NW–SE direction [33].

The Nekor ENE–WSW sinistral fault is the main structure of this region, which is more than 50 km long and cuts the coast at Ras Afraou, and was formed during its establishment to the SW from the Internal Zone to the Tortonian one [34, 35]. The most recent and active structures observed at the surface are normal N–S faults, with a minor declining component [36–38]. The maximum value of the recorded magnitude in this region from 1900 to 2007 is 6.3 [39].

Deformation at depth is affected by the NW–SE convergence of Eurasia and Africa, with the development of large N–S seismic faults at the level of the rigid base. It is these faults, which are not outcrop ones, that are responsible for the main seismic risk in the region.

To simplify the calculation of seismic loads and standardize design requirements for structures across large areas of the country, the Moroccan seismic code [39] uses a zoning approach.

In order to properly identify the particular character of an earthquake at a given location, this regulation adopts separate zoning for the Amax (maximum acceleration) and Vmax (maximum velocity) parameters, expressed in fractions of 1 g and 1 m/s, respectively. Each of the two seismic zoning maps adopted by the Moroccan seismic code currently has five zones (0–4). Our study area is classified in a zone (Zv: 4) of a velocity equal to 0.17 m/s, and in an acceleration that is classified (Za: 4) by an acceleration equal to 0.18 g [39].

Methodology

The first methodological step in this work was the delimitation of the study area (Fig. 1), ensuring that the study area included all areas of the major development project at the Marchica Lagoon site. Afterward we started collecting data related to the geology and geotechnics of the area; during this stage, we were able to have geological maps, digital elevation model (remote-sensed data from satellites), geological information, hydrology, hydrogeology and tectonics of the area. During this phase, extensive geotechnical data collection is done from public and private organizations with civil engineering projects, other boreholes, and in situ and laboratory tests have been done to provide a significant quantity of data sufficient to meet the objectives of this work. Based on geotechnical data (boreholes, grain size analysis, water content of soil, wet density, methylene blue test, atterberg limits, pressumeter test, direct shear test, consolidation test, standard penetration test, cone penetration test, waves shear velocity), a classification and identification of the layers present in the study area with variable depths.

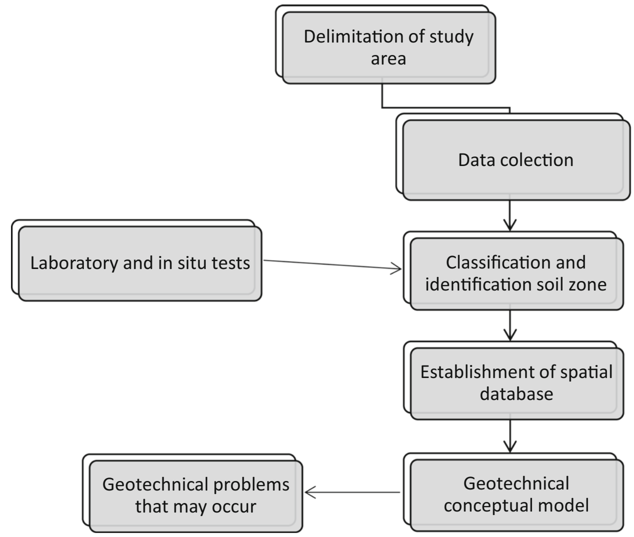

Fig. 3 Flowchart of the study steps

To have an easy readability of geotechnical results, that will permit us to subsequently create geotechnical models representing areas that have similar geotechnical characteristics, a spatial database has been created, it contains the result of the digitization of maps, attractive databases containing the glued information, and raster images of the study area. The last part of this work consists in detecting the geotechnical problems likely to occur in this area. We will study the bearing capacity of the soil, compressibility and settlement, and liquefaction (Fig. 3).

Results

Geotechnical Characterization of the Study Area: Geotechnical Model

Geotechnical mapping is usually based on the data available on the area, such as maps, geotechnical reports, and surveys, etc. The study area is relatively large, which is beneficial for has an advantage of the probability of collecting a large amount of data, and disadvantageous for the lack of homogeneous coverage of the area, because civil engineering projects are generally concentrated in urbanized areas. Several geotechnical investigation campaigns have made it possible to carry out field tests of many different types (core drilling, pits and pressuremeter soundings), as well as a lot of identification and mechanical laboratory tests. Geotechnical characterization is established for each zone separately (Fig. 4).

Barrier Zone (Lido)

The barrier zone is characterized by a lithology composed by a vegetal cover and/or grade materials with thicknesses ranging from 0.15 to 0.80 m, this cover was not found in the shallow boreholes PM4, PM8 et PM9. This layer overlaps another layer composed of sand with shells containing locally, traces of silt in the shallow boreholes PM2, PM10, PM11, and PM13. The water table level varies from 0.2 to 1.2 m below the natural ground level. According to the results of the tests carried out, the analyzed soils are generally classified as poor graded clean sand. The diagram below shows the overall lithology and geotechnical characteristics of the barrier zone.

Bou-Areg and Arekman Zone

This zone is characterized by a lithology constituted by a top layer of topsoil or locally gravelly backfill with a variable thickness that ranges between 0.2 and 0.5 m. Under this layer, there are silty sands located only to the right of the PM3 borehole. This layer of sand is characterized by a thickness of around 1.4 m and a low fines content (28.6% $<$ 0.08 mm), and a VBS value equal to 0.76, which means that it is slightly sensitive to water. At the same level of this layer, there is a layer of clayey gravel, only located to the right of the PM1 borehole with a low fines content (10.4% $<$ 0.08 mm), slight sensitivity to water (VBS = 0,60) and low plasticity. The lower layer encountered in this zone is a layer of silty clay, which is moderately plastic, found in all the shallow boreholes except in for PM1 and PM3, the fines content is very high (between 62.9 and 93.4), this layer is also sensitive to water (1.26 $<$ VBS $<$ 2.7).

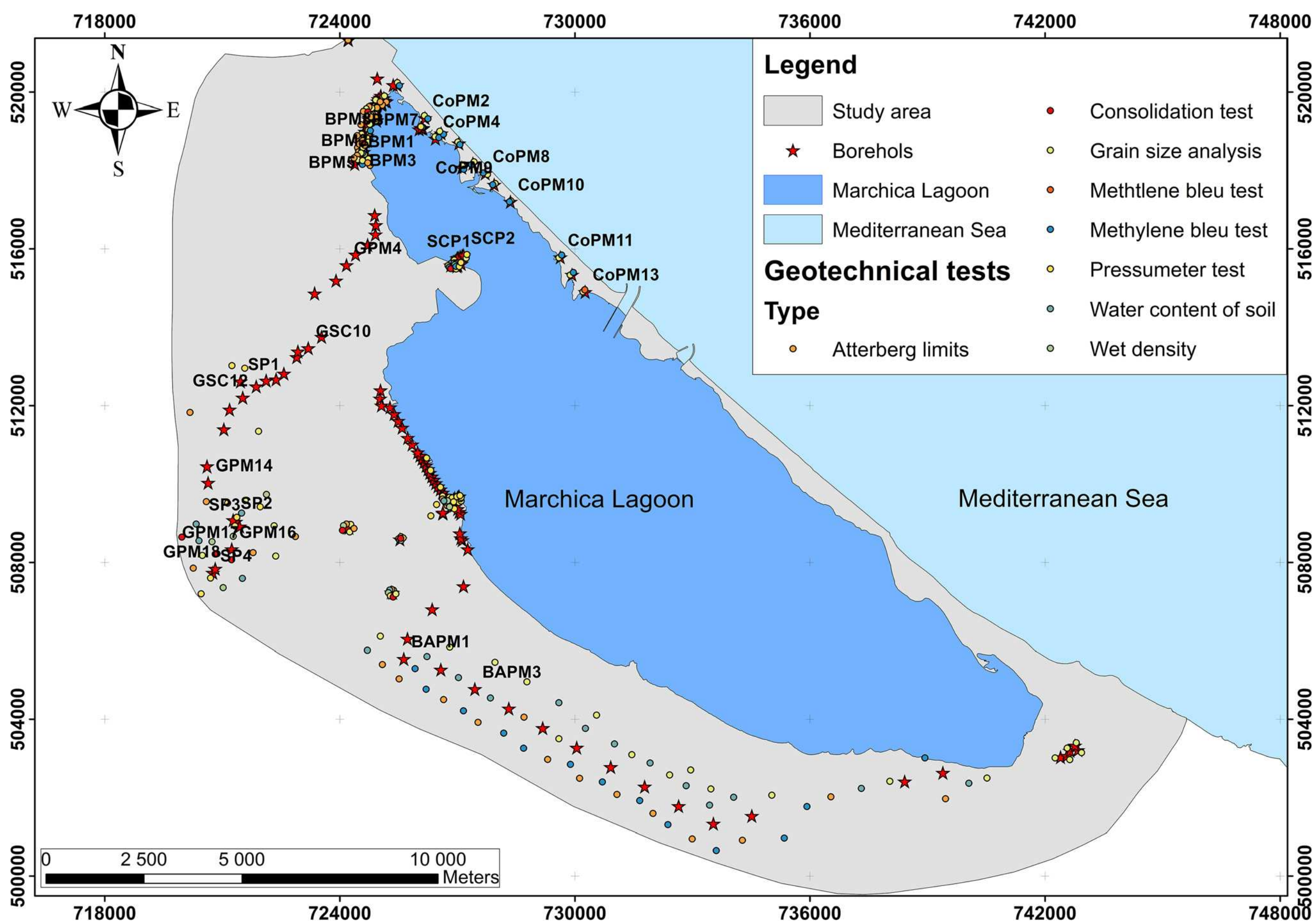

Fig. 4 Location of several geotechnical tests and boreholes

Gourougou Zone

The lithology of this area consists of 4 main formations; a topsoil or silty clay cover with varying thicknesses from 0.1 to 1.6 m. An underlying layer of low-plastic clayey silt located in the PM14, PM16, PM17 and PM18 boreholes, with a thickness between 1.7 and 4 m. Below this layer, another layer of blocks resulting from the alteration of volcanic rocks, with a clay-silty matrix is found with a variable thickness (between 0.5 and 6 m), and it is encountered in the area of the PM4, CS10 and SC12 boreholes. The base layer is a layer of highly fractured to hard volcanic rock and is found in all the boreholes except for PM16, PM17 and MP18.

Atalayoun Zone

According to the boreholes carried out, the lithology of the site generally consists of:

- A cover of sandy silt or silty sand with a thickness of 1.0 to 2.0 m, this layer is characterized by a rather fine granularity (72% $<$ 0.08 mm), a low plasticity (IP = 6) and a VBS value of = 1.13.
- A layer of varying thickness between 2.0 and 8.5 m of soft clay, in this layer the fines fraction is dominant (between 72 and 100% $<$ 0.08 mm), and the sandy fraction is weak (0.08 mm $<$ 26% $<$ 2 mm). The plasticity of this layer is high (18 $<$ IP $<$ 35) and the liquid limit (Wl) is between 3 and 63%. The dry density of this layer is low (0.9–1.1 t/m^3) for a high natural water content ranging from 23 to 57%, which shows that the layer is compressible and saturated. The oedometric characteristics show that it is a very compressible soil, with a general compressibility index (Cc) of 0.4 of a underconsolidated soil, with a preconsolidation pressure (σ'_p) of 21 to 30 kPa, and a consolidation coefficient (Cv) ranging from 1.25×10^{-7} to 6.82×10^{-9} m^2/s. Therefore, these are the characteristics of compressible clay soils.
  The shear tests showed an abnormally high angle of internal friction (ϕ') and cohesion (C'), with: ϕ' = 11°–29°, C' = 7–17 kPa, ϕu = 27°–43°, Cu = 7–30 kPa.
- A lower layer that has a roof which oscillates between depths of 8.5 m and 21.0 m consisting of a clayey marl characterized by a fine granularity, with a percentage of fine elements ranging from 54 to 73% for a sandy fraction (class 0.08 mm/2 mm) ranging from 11 to 30% and a proportion of elements $>$ 2 mm low from 7 to 35% and a very high plasticity with an index between 30 and 38, for a liquidity limit of in the order 60%. From in situ data, this layer is marked by an average dry density of between 1.41 and 1.53 t/m^3, a quite high natural water content, ranging from 27 to 29%, attesting that it is a moderately compact and saturated soil. The oedometric characteristics show that this soil is moderately compressible, with a compressibility index of 0.2; and consolidated with a high preconsolidation pressure ranging from 275 to 375 kPa. The shear tests showed a mean friction angle and cohesion, with: ϕ' = 20°, C' = 11 kPa.

Beni-Nsar Zone

The lithology of the Beni-Ansar area is heterogeneous and is modeled on the following lithological profile:

- A cover of topsoil or heterogeneous backfill of a thickness of 0.4 to 1.0 m. It is encountered at the right of the PM2, PM3, PM6, PM7 and PM8 boreholes. In the area of the PM10, PM11, PM12, PM13 and PM14 boreholes, the backfill is of gravelly type whose thickness varies from 0.5 to 2.3 m.
- An underlying layer composed of clayey silt or brownish clay which are quite tuffaceous and located along the line from the PM1 to PM5 boreholes over a thickness from 0.4 to 1.55 m. This layer is characterized by an average fines content of (45.4% to 46.4% $<$ 0.08 mm), it should also be noted that materials passing through a 2 mm sieve are in the order of 68.7% to 7.6%. The plasticity is moderate, with a plasticity index of about 20. The liquidity limit oscillates from 28 to 54%.
- A horizon composed of fine sands is found in the PM6, PM7 and PM8 boreholes. Its thickness is in the order of 0.5 m. The fines content is low (21.2% $<$ 0.08 mm), and the elements passing through the 2 mm sieve have a percentage of 91.2%.
- An underlying layer of gravel with a sandy-silty or sandy-clay matrix. Its thickness is variable depending on the zones; it was not limited to the PM1, PM2 and PM3 boreholes zone, there are also a few centimeters in the PM5 and PM8 boreholes area. The fines content is low; however, the refusals at 2 mm are dominant between 63.7 and 73.3%. Its plasticity is average to locally high, with an index of 12–32 for a liquid limit in the range of 31–67%.
- A lower layer consisting of clays and silts which are less to very plastic, characterized by a fines content of 48.1–85.2%, and the elements which have a particle size greater than 2 mm are very low. The plasticity index varies from 19 to 31 for a liquid limit of 41–66%, which indicates moderate to high plasticity.

The oedometric characteristics show that it is a normally consolidated soil, and compressible to very compressible, with a compressibility index of 0.152–0.315. The swelling index is in the order of 0.04–0.08, which indicates that swelling is not very high.

The shear tests showed an angle of friction and cohesion as follows: $\phi' = 9.2°$, $C' = 30.4$ kPa.

In the Beni-Nsar zone and moving away from the lagoon, there is a lateral change of facies, which is normal in littoral zones; the two following layers are increasingly dominant:

- A gravelly backfill with clay-silty matrix.
- A lower layer of gravel with clay-sandy matrix.

The following table summarizes the results of the most significant geotechnical parameters for each zone to provide a more comprehensive view of the study area (Table 1).

Geotechnical mapping requires detailed spatial analysis to determine the distribution of geotechnical formations. Dominant geotechnical formations are mostly covered by a major layer of backfill or topsoil, that covers most of the site, which leads to confusion between the true dominant facies and the cover formations. To solve this problem, we based our spatial analysis on the data collected from several geotechnical surveys, and from which a geotechnical database was created over an area of 236 km^2 using geographical database management software (ArcGIS) (Fig. 5).

Site Effect of an Earthquake in the Study Area

The local seismic hazard assessment (the determination of fundamental period and shear wave velocity) depends on the geological and geotechnical characteristics of the site and contributes significantly to seismic risk assessment.

We have determined the fundamental frequency [40] using a three-component seismometer to record background noise to calculate the ratio of the spectrum of the horizontal component to the vertical component. Thus, the fundamental frequency for each geological formation was determined (see Table 2 and Fig. 6), using the Nakamura method [40, 41] in order to predict the susceptibility of the site effect (amplification of earth seismic motion). The results show that the fundamental frequency varies between 0.27 and 2.80 Hz (see Table 2). The low values correspond to the soft geological formations of the Quaternary age (Zone I, Zone II and Zone IV). Zone I corresponds to the sandy barrier, zone II (Beni-Ansar) is characterized by the abundance of gravelly clay soils resulting from erosion and the alteration of the volcanic rocks constituting the catchment area of this zone; and zone IV corresponds to the plain of Bou-Areg which is filled by a thick layer of clay. While the high value (2.80 Hz) corresponds to the basaltic volcanic formation (Zone III).

According to the Moroccan seismic code [39], the value of the acceleration (A_{max}) in the study area is 0.18 g, which corresponds to the value of the substratum. The acceleration value of the different formations is determined by multiplying the value 0.18 g by the coefficient of each formation (site effect). Acceleration values are shown in Table 3, varying between 0.18 and 0.32 g.

Table 1 Most significant geotechnical data for each area

Zones	Lithology	Depth (m)	Gran size analyses (%)			Ip (%)	ϒ (kg/m^3)	*C* (Kpa)	ϕ (°)	VBS
			$d > 2$	$2 > d > 0.08$	$d < 0.08$					
Barrier (Lido)	Sand	0.4–3.0	12.5 ± 7.5	85 ± 10	4 ± 3.5	–	1850 ± 50	–	33	0.07 ± 0.01
Bou-Areg and Arekman	Silty clay	0.25–1.7	5 ± 4	21 ± 9	78 ± 11	18 ± 3	1550 ± 50	17.5 ± 3.4	21.4 ± 3	1.4 ± 0.4
Gourougou	Clayey silt	1.0–4.0	9 ± 5	29 ± 12	59 ± 20	17 ± 2	1680 ± 110	28.3 ± 5.3	19.3 ± 0.7	–
	Volcanic rock	4.0–21.0	–	–	–	–	2340 ± 130	–	–	–
Atalayoun	Clay	1.5–8.5	0	7 ± 7	93 ± 7	22 ± 4	995 ± 95	18.5 ± 11.5	35 ± 8	2.77 ± 1.29
	Clayey marl	8.5–21	56 ± 16	20 ± 10	5 ± 3.5	34 ± 4	1470 ± 60	11	20	2.67 ± 2.91
Beni-Nsar	Silty clay	0.7–3.2	65 ± 20	29.5 ± 9.5	7 ± 6.5	19.5 ± 5.5	1510	30.4	9.2	–
	Gravel clay-sandy matrix	0.3–3.0	14.4 ± 1.4	16.2 ± 3.5	69.4 ± 4.9	14.5 ± 0.5	1860	–	–	0.45 ± 0.01

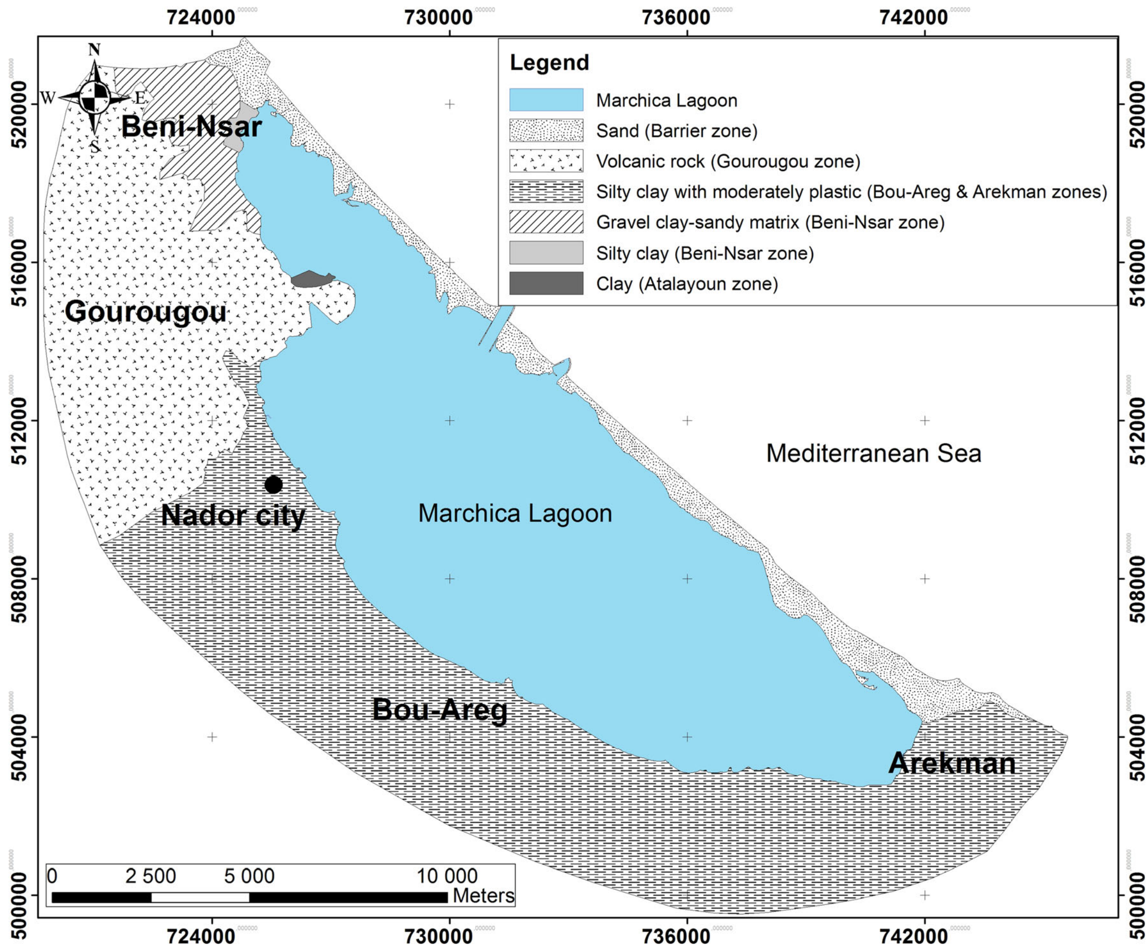

Fig. 5 Simplified geotechnical map based on dominant geological facies of the study area

Table 2 Frequencies and periods of the soils in the four zones

Zone	Frequency (Hz)	Period (s)
I	0.63	1.59
II	0.27	3.77
III	2.80	0.36
IV	0.56	1.79

Possible Associated Geotechnical Problems

Bearing Capacity of the Soil

The problem of low bearing capacity is directly related to the mechanical properties of the soil derived from laboratory and in situ tests. For an estimation of the bearing capacity in our study area, we have to fix the type of construction and the type of foundations, as well as some dimensions of the foundations. The constraints applied by the constructions, and which are really transmitted to the ground by the foundations, must be compatible with the risk of rupture of the ground located under the foundations, and induce only minimum settlements eligible for each type of construction. Many scientists [42–45] have long worked on determining the bearing capacity of different types of soils for supporting different types of foundations, based on several tests in the laboratory or in situ.

Several research projects have been carried out to produce bearing capacity maps with regard to building loads [1, 46, 47]. The lift values that we used for the establishment of the bearing capacity map are taken from the geotechnical reports of the buildings already constructed, these buildings were based on isolated shallow foundations, a square shape of 1 m from the side and around 1.5 m anchorage in the ground. The civil engineering laboratories that carried out these geotechnical reports used the Eurocode 7 geotechnical calculation regulations (Fig. 7).

During the bearing capacity study of soils covering the study area, we have been able to conclude that the ground in the area of the plain of Bou-Areg and Beni-Nsar is characterized by an average to low bearing capacity. It was

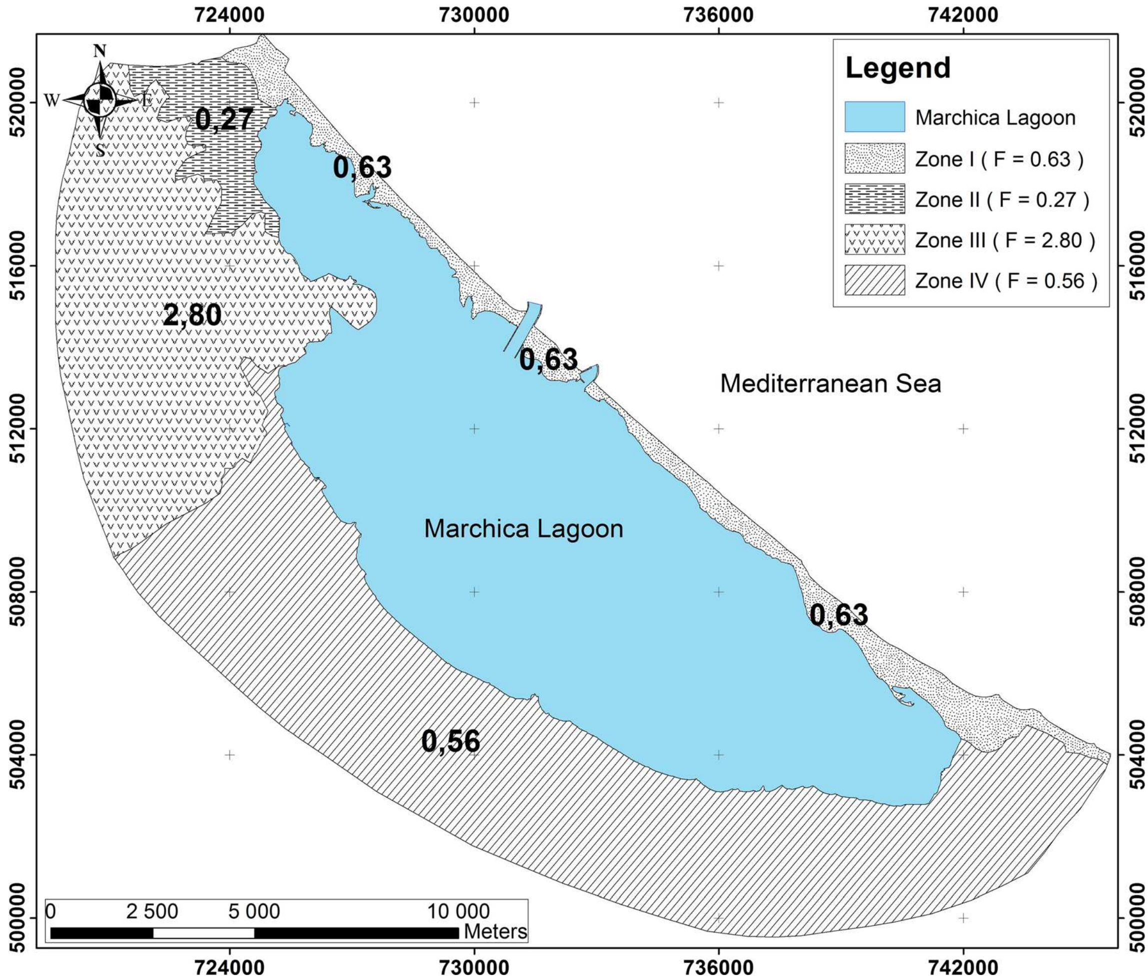

Fig. 6 Seismic microzonification in the study area (*F* fundamental frequency)

Table 3 Maximum predictable acceleration in the different geotechnical zones

Zone	Coefficient of site	A_{max}
I	1.4	0.25
II	1.4	0.25
III	1	0.18
IV	1.8	0.32

difficult to identify the limit of these two zones, due to the heterogeneity of quaternary deposits of a clay-silty nature.

The heterogeneity of quaternary deposits constitutes an imminent risk on buildings located on this type of soil, because of the considerable variation in the geotechnical properties of the soil over short distances, which produces a risk of high differential settlement. The risk of differential settlement is closely related to the size of the loads and the type of foundation adopted and its dimensions.

In the case of buildings with very high permanent and operational loads, it is necessary to adopt deep foundations, which reach the substratum of the area. Additional geotechnical boreholes must locate the depth of the substratum.

Soil Settlement

Soil consists of three phases, solid, liquid and gaseous, soil is similarly deformable to every material that bends under a load; in general, the displacement of soil particles under the effect of a load is made according to the three directions of the space; vertical displacement is called settlement, and horizontal components are called horizontal displacements. The settlement in a soil is influenced by many parameters such as the nature of the soil, the thickness of the compressible layer, compressibility of the soil, and the permeability of the soil.

Oedometric tests were used to obtain the compressibility characteristics of the soil. The area of the Beni-Nsar corniche has an abundance of clay and silts which are in the

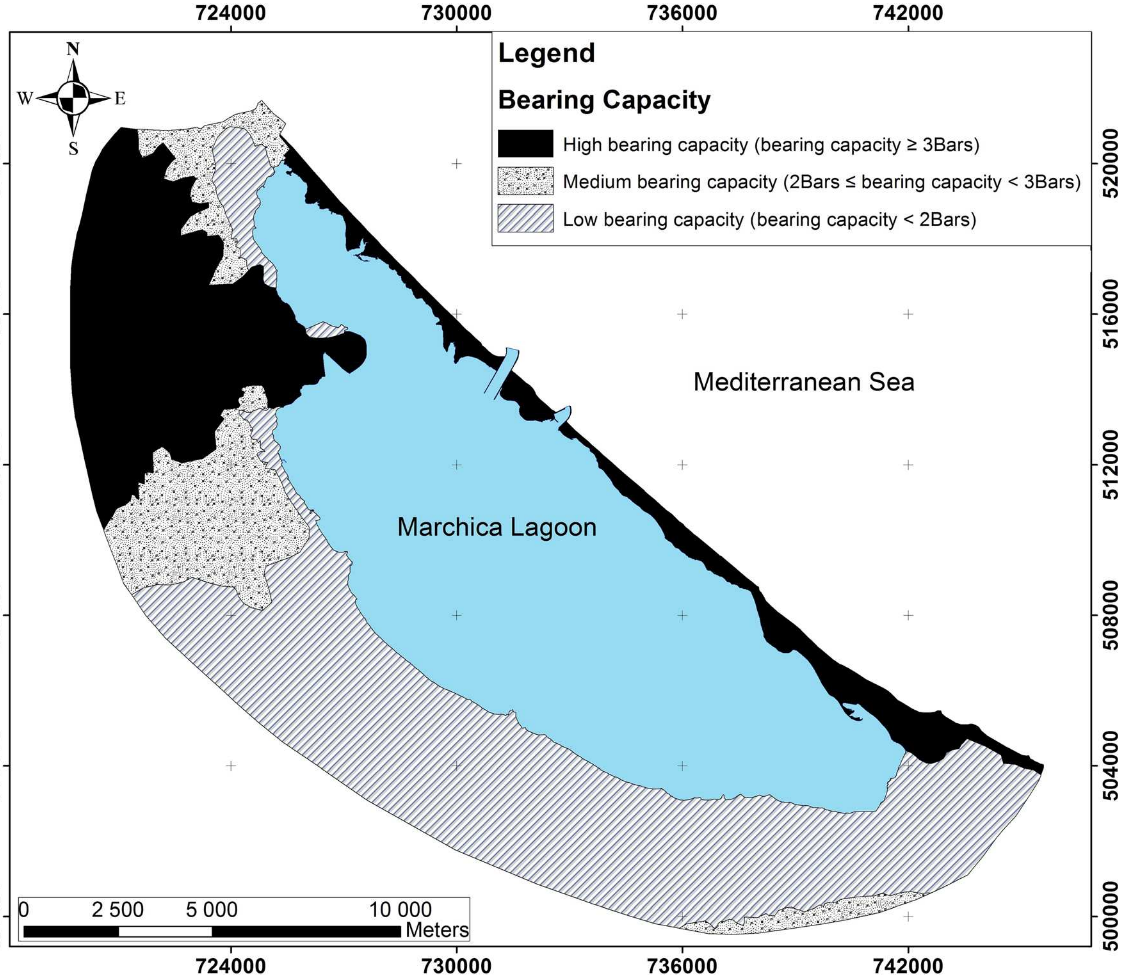

Fig. 7 Bearing capacity map in the study area

form of a layer of a depth between 2 and 3.5 m or more, normally consolidated with a variable compressibility index between 0.152 and 0.315, which means that the soil is compressible to very compressible. In the Atalayoun zone, the compressibility index is between 0.2 and 0.4, which indicates that the soil is very compressible. The dry density is also low, 0.900 t/m^3, this layer of reddish clay is underconsolidated because of its very recent age, returning to the history of the area before it was backfilled. It can be seen that the site served as a basin for the retention and decantation of iron mine wash water, these sediments deposited during the mining activity (from 1914 to 1976) did not generate large loads to be consolidated. The last area with a risk of settlement is the Bou-Areg plateau, which extends from Nador to Arekman. This area is known for its agricultural activity, below the topsoil layer there is a layer of normally consolidated silty clay with a compressibility index varying from 0.1 to 0.2, which means that this layer is moderately compressible.

Susceptibility to Soil Liquefaction Using Different Criteria (Cramer, 1996)

The phenomenon of soil liquefaction occurs when the shear strength of a soil is reduced by rapid loading, such as in the case of a seismic process. This phenomenon takes place in soils saturated with water. Before the production of the seismic load, the pore water pressure is relatively low, while during the earthquake the interstitial water pressure can increase considerably to a point where the grains constituting the soil can be moved easily. Liquefaction occurs when the pore water pressure increases to approach containment pressure, thereby reducing or eliminating the effective soil stresses.

The first step for a liquefaction analysis is to determine the susceptibility of the soil to liquefaction in the event of an earthquake. The majority of soils sensitive to liquefaction are powdery soils. Cohesive soils only liquefy under specific conditions [48]. The criteria for determining the susceptibility to liquefaction of a soil are very varied. For example, the criteria adopted by Kramer [49].

Historical criteria A large amount of information can be obtained about the susceptibility to liquefaction of certain types of soils by returning to earthquakes that were produced in the past. Soils that were liquefied in the past can still experience the same phenomenon in future earthquakes, the study of previous earthquakes can provide us with reliable and very important information.

Geological criteria The geological process of the formation of a soil deposit can give us an idea of its susceptibility to liquefaction. Sediment deposits from fluvial or wind transport in a saturated environment may be highly susceptible to liquefaction. This high susceptibility is due to the sorting of particles into grains of a uniform size in a loose state that tends to become denser once shaken by an earthquake. Embankments made by the process of hydraulic filling may also be susceptible to liquefaction.

Compositional criteria Soils consisting of particles that are about the same size are more susceptible to liquefaction than soils with a range of specific sizes. If the soil particles are of different sizes, the small particles tend to position themselves in the voids between the larger particles, thereby reducing the density and the development of the interstitial pressure when subjected to an earthquake. A soil deposit consisting of angular particles is normally less susceptible to liquefaction because of its high resistance to friction, which is due to the rough surface of the particles. Historically, sandy soils were considered as the only type of soil susceptible to liquefaction, but liquefaction has also been observed in silt and gravel. Fine soils are susceptible to this type of behavior if they meet the following criteria [50].

- Fines Fraction lower than 0.005 mm $< 15\%$
- Liquid limit (LL) $< 35\%$
- Water Content > 0.9 LL

Ground condition criteria By setting the density, soils that have low effective stresses are generally more susceptible to liquefaction than soils that have high effective stresses.

Based on the previous criteria, Table 4 summarizes the evaluation of the study area with respect to susceptibility to liquefaction. There are three areas which are susceptible to liquefaction because of their criteria.

The particle size characteristics of the barrier zone indicate, by the uniformity coefficient, which is generally less than three, that the particle size is uniform and, therefore, the sands of this area are susceptible to liquefaction. The shape of sands of marine origin is often rounded, which decreases their resistance to intergranular friction and, consequently, increases their susceptibility to liquefaction.

Liquefaction Evaluation Using Safety Factor Methods

Using Cramer's method, the areas that are likely to liquefy (Fig. 8) are the barrier zone, the Bou-Areg, Arekman zone and the Atalayoun zone. According to the data available, we used a liquefaction evaluation method using safety factor for each zone.

After treatment of the test results using all the corrections necessary to adapt the calculations of cyclic stress to an earthquake with a magnitude of 6.5, which is close to the maximum magnitude recorded in the zone in 2016 according to the United States Geological Survey. The resistance of the soil to liquefaction must also be corrected to represent the properties of the soils in place. The liquefaction potential was determined from the comparison of the Cyclic Resistance Ratio (CRR) of the soil and the cyclic stress ratio (CSR) of the earthquake.

The liquefaction potential in the Atalayoun area has been evaluated using the method based on the CPT test. Eight CPT tests were carried out in the Atalayoun area to produce continuous profiles of resistance to cone penetration into the soil at depths between 6 and 10 m. Figure 9 shows an example of the variation profile of soil resistance to cone depression, CRR and CSR.

In the Bou-Areg and Arekman zones, the risk of liquefaction was determined by eight SPT tests distributed over the area and in the vicinity of large cities where liquefaction can produce a lot of damage. In each survey, the test is carried out with a vertical interval of about 1.5 m. Figure 10 shows an example of the profile produced by the STP test, as well as the CRR and the CSR ones.

The third most well-known method for assessing liquefaction is the geophysical method that allows us to determine the velocity of seismic shear waves. We used the H/V technique which gives us an estimate of the seismic wave shear rate. This technique has recently been used and confirmed by [51]. Three profiles were made in the barrier zone to obtain a synthetic profile (Fig. 11) of the variation of the propagation velocity of the seismic waves in the barrierzone.

Figure 11 shows the first 40 m of the variation profile of the propagation velocity of shear seismic waves, as well as the CRR and the CSR of the barrierzone.

After analyzing all the results of the determination of the liquefaction potential of the soil in the areas likely to liquefy, it turned out that in the Atalayoun zone, which is dominated by clay soil, the soil resistance to cyclic stresses is much higher than the cyclic shear stress produced by a possible earthquake of a magnitude of less than, or equal to, 6.5. This leads us to conclude that the liquefaction potential in this zone is zero. In the Bou-Areg zone, which stretches between Nador and Arekman, where the soil is silty clay, we used eight SPT boreholes to calculate the soil

Table 4 Evaluation of liquefaction susceptibility following different criteria established by Cramer, 1996

Zones	Historical criteria	Geological criteria	Compositional criteria	Ground condition criteria
The barrier zone (Lido)	–	X	X	–
The Bou-Areg and Arekman zone	–	X	–	–
The Gourougou zone	–	–	–	–
The Atalayoun zone	–	X	X	X
The Beni-Nsar zone	–	–	–	–

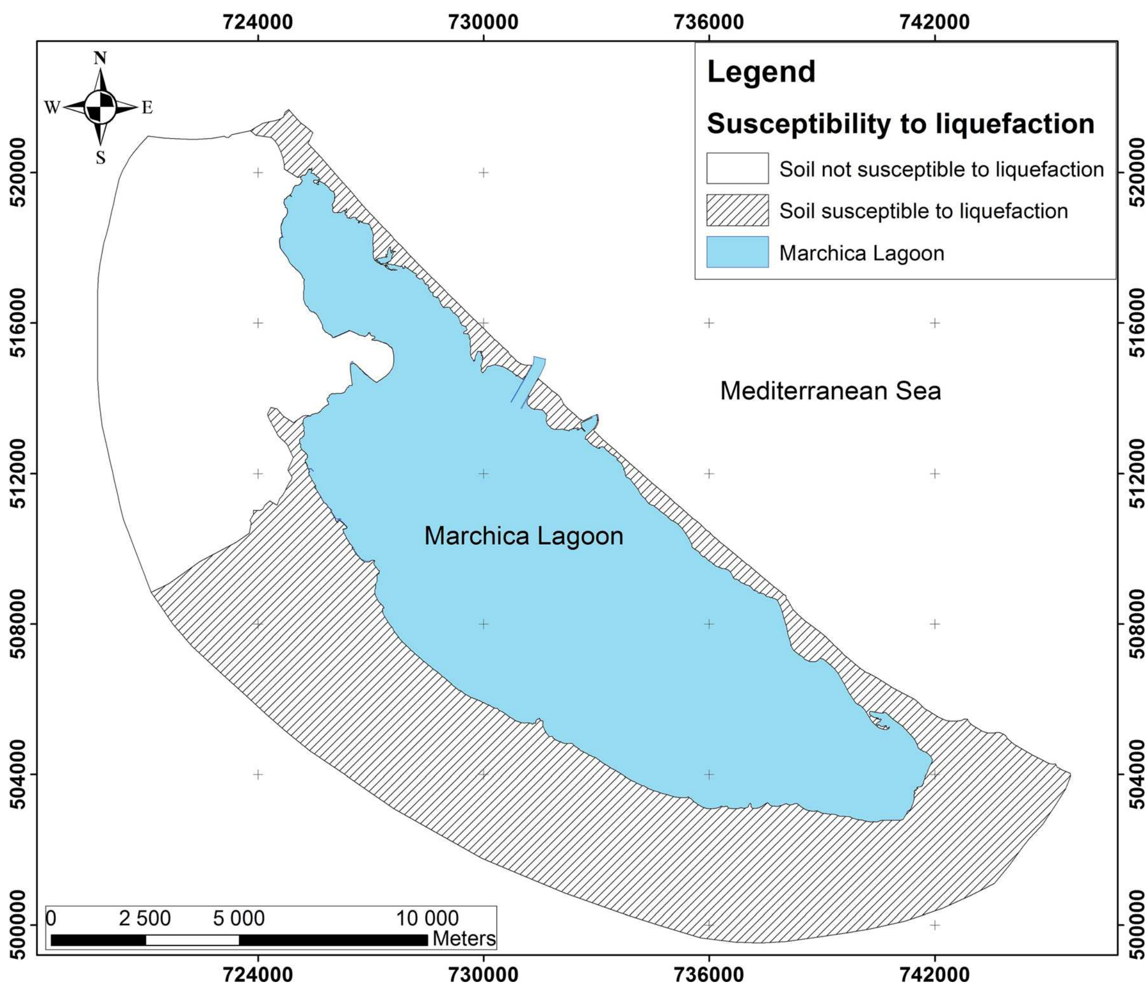

Fig. 8 Soil liquefaction susceptibility map using Cramer (1996)'s criteria

CRR and then compare it with the CSR, and after comparing these results, we noticed that the susceptibility to liquefaction in this zone is also zero. The third zone where the calculation of the susceptibility to liquefaction was made, is the barrier (cordon) zone which separates the Marchica lagoon from the Mediterranean Sea. According to the estimation results of the seismic wave shear rate using the H/V technique, it is clear that the CRR is much larger than the CSR, which allows us to say that the potential of liquefaction is low, the velocity increases with depth, and that CRR always remains higher than CSR, with approximation at some depths.

Discussion

The study area is a good example to be studied as a complex geotechnical area, with significant urban extension and exceptional natural assets, which have made the area a suitable location for the Marchica lagoon site

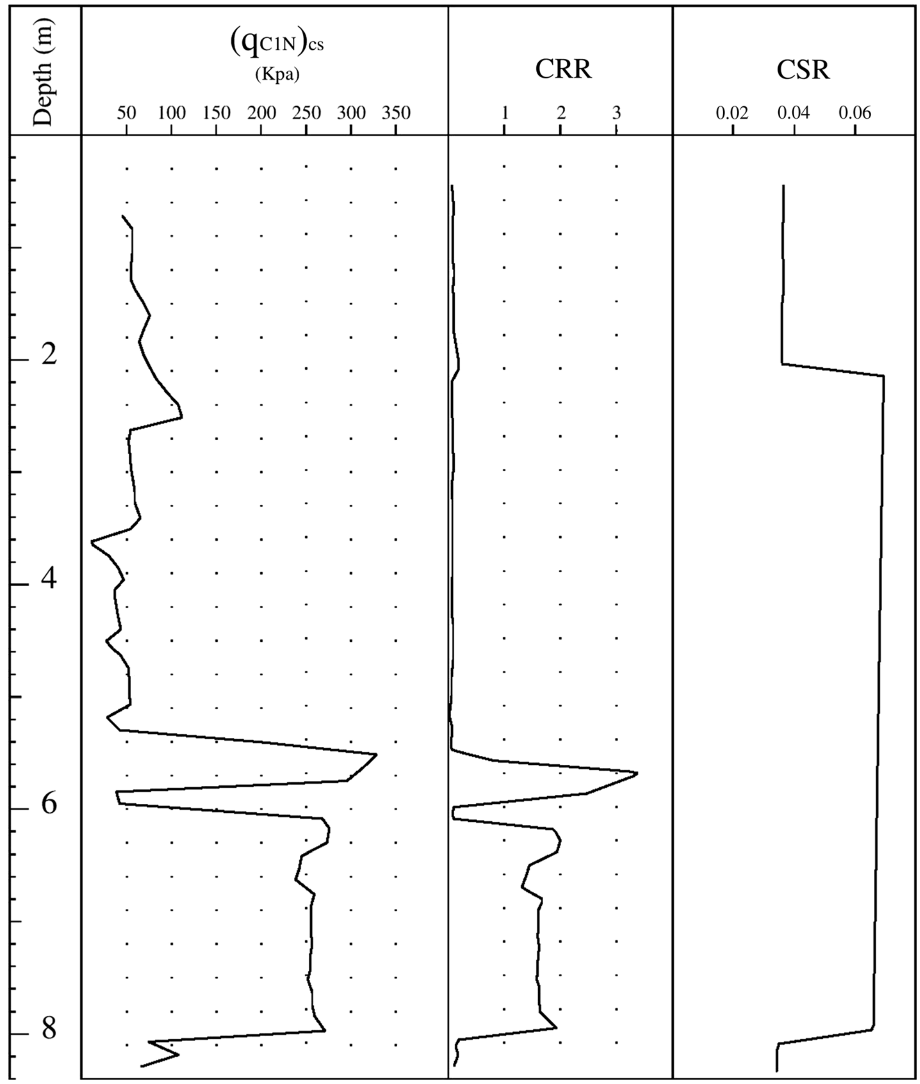

Fig. 9 Typical profile of cone penetration test, CRR and CSR in Atalayoun zone

development project. Planners and decision-makers in charge of the management of this project need a useful support that shows the geotechnical zoning, for safe urban extension and efficient project management. In this work, we have tried to integrate some factors that control the stability of the buildings and that are related to geology starting by lithology, lithological site effect (amplification of seismic waves), and soil bearing capacity, susceptibility to settlement and ending with susceptibility to liquefaction.

Soil characterization by the fundamental frequency is the most adequate means to estimate the amplification of the soil at the local level. The region studied is known for the seismic instability that characterizes the Alboran Sea area, induced by the collision between the African and Eurasian plates. The results show different frequency values, and it is mainly related to the diverse types of sediments of different depth. The low frequency values show that the region can have the phenomenon of amplification during an earthquake, especially in basins with flat topography and thick sediments. For the Gourougou region where the volcanic bedrock is located, no amplification is expected, as the ground fundamental frequency is relatively high, which refers to the absence of lithological site effect in this area.

The soil bearing capacity is a very important parameter to guarantee the stability of the constructions, it gives the planners an idea of the permanent and operating loads that the soil can support without having inadmissible deformations, the bearing capacity of the soil also guides us for the choice of the foundation system of the buildings (surface and depth). We see the results of the soil bearing capacity in the study area. The majority of the area has low bearing capacities, which can be interpreted by the dominance of fine soils in the area; the nature of the soft and fine deposits increases the risk of having other problems.

The results of consolidation tests have shown that the soils in place are normally consolidated in all areas where fine soils are present, except in the Atalayoun zone where

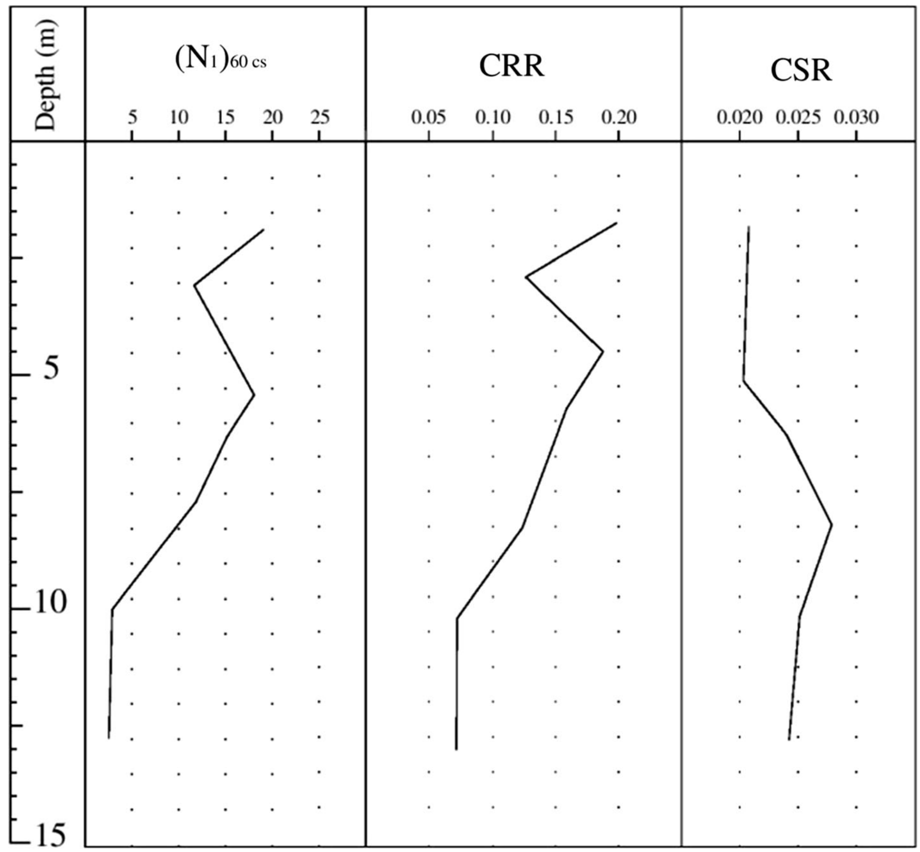

Fig. 10 Typical profile of standard penetration test, CRR and CSR in Bou-Areg and Arekman zones

the fine soils are underconsolidated, the geological history of the region confirms the results, the deposits of the fine soils are of recent quaternary age, and they have not undergone confinement during the past, they have had sufficient time for this consolidation under the effect of their own weight, Concerning the clay in the Atalayoun area, the results of underconsolidation of the soil are due to the recent entropic nature of the deposit.

In this work, the risk of compaction is also studied based on the compressibility index, the soils most susceptible to this compaction are the fine soils of the Nador, Arekman, and Atalayoun zones, these results are due to the size of the particles and their low permeability which prevents the intergranular water from escaping quickly under the effective vertical stress of soil, so when the soil is overloaded there will be compaction that continues for a long period of time and is the most dangerous for construction.

The results of this work indicate the most and least dangerous areas for the realisation of development projects on the Marchica lagoon site. Comparing our results with other works in similar areas from the geographical and environmental point of view, we find that there are many points in common; for example: El May M. et al worked on the area of the Tunisian capital in 2010. Our two study areas are located on the coast of the southern shore of the Mediterranean Sea, with almost identical geotechnical context; we were able to detect almost the same geotechnical problems. We can conclude from this comparison between our results and other work that the approach followed in this work can be used in other coastal areas that have similar environments.

This work is a very useful support to the actors of the great development project of the Marchica lagoon site, it can be used at several stages of the decision-making process.It will allow the decision-makers in charge of the project management to have a regional vision of the geotechnical conditions of the area, and to make an optimal choice of the construction site for each project. This work will also be very useful to geotechnical engineers, during the geotechnical investigation phase. The results in the form of a map form an important basis for future urban planning. Currently, there is no other source of geotechnical data at the regional scale, which gives this work a very important utility and impact.

As a perspective, it is proposed to carry out a geotechnical micro-zoning of the urban areas located in the study area, targeting mainly the cities of Nador and Beni Ensar, in order to have a better resolution in terms of geotechnical information.

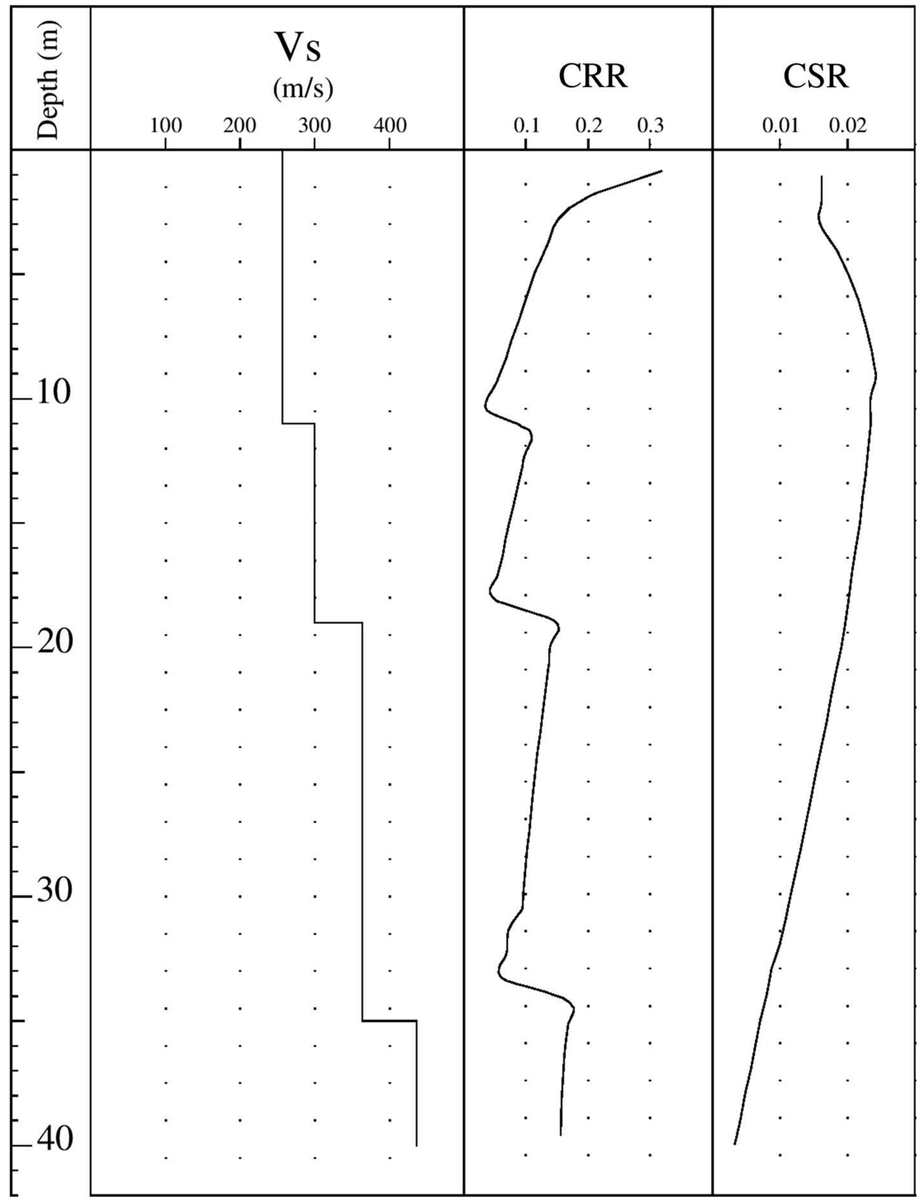

Fig. 11 Profile of the velocity of seismic shear waves, CRR and CSR in the barrier zone

Conclusion

This work displays a global geotechnical characterization of all zones of the Marchica Lagoon area for the first time. Indeed, it is based on all the tests carried in the Marchica Lagoon site during the last 2 years.

This study attempts to create a simple geotechnical model of the Marchica Lagoon area with the objective of identifying the main geotechnical issues likely to occur in this area. This work will allow better programming in geotechnical reconnaissance campaigns, as well as an optimal choice of geotechnical investigation techniques for future civil engineering works.

Five main zones with similar geotechnical characteristics have been identified:

The barrier zone is the only zone with an abundance of poorly graded sand that can reach important depths (> 30 m); this thick layer of sand is due to its contact with the Mediterranean Sea.

The Gourougou area is an especially high zone, which can reach 800 m. It is characterized by a volcanic substratum overcome by a clay silt layer resulting from source rock weathering. This superficial layer, with a thickness of 1–4 m, is characterized by a fines content (< 0.08 mm) of 60%, and a plasticity index equal to 17, which means that this layer not very plastic.

The Bou-Areg and Arekman zone represents a favorable environment for the sedimentation of weathering and mechanical disintegration products from the surrounding mountains. It is constituted of silty clays that can reach

30 m. The fines content of this layer is high (80%) and it has major sensitivity to water, with a coefficient of the VBS test in the vicinity of 1.4.

The Atalayoun zone is a geotechnically unfavorable zone, the plasticity of the clay deposit which can reach a thickness of 8.5 m is relatively high (IP = 22), and with a density of 990 kg/m^3, this type of soil can create serious geotechnical problems.

The first geotechnical problem detected by the oedometric test is the settlement phenomenon, which occurs mainly in the Beni-Nsar corniche where the compressibility index varies between 0.152 and 0.315, indicating a compressible to very compressible soil. This phenomenon is also encountered in the Atalayoun zone in which the compressibility index varying between 0.2 and 0.4 indicates a very compressible soil. Another problem which is closely linked to the first problem is low bearing capacity, this problem was encountered in the areas of the Bou-Areg plain, Arekmane, Nador and Beni-Ensar, and the low bearing capacity (between 1 and 2 bars) of the fine soils that characterize these zones.

The third geotechnical problem is the liquefaction susceptibility of soils in the area. It was firstly determined by four criteria: historical, geological, compositional, and soil condition. Then, we proceeded to the determination of the liquefaction potential using the penetrometer tests (CPT and SPT), and also using the estimation of the shear wave velocity. The analysis of these indexes shows that the liquefaction potential is very low in all areas of the Marchica lagoon, with the exception of the barrier zone where all conditions are favorable for liquefaction, and where this phenomenon is classified as low.

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Compliance with Ethical Standards

Conflict of interest The authors declare that they have no conflict of interest.

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