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A database for the offshore geotechnical site characterization of Italian seas

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ABSTRACT: Italy counts around 8300 km of coasts, including its islands, making marine activities crucial for the development of its economy. Increasing interest has been devoted to the offshore energy sector, where Italy has a brief tradition in the Oil and Gas industry and it is now opening to the possibility of an offshore renewable market. From this perspective, the most promising source is certainly represented by offshore wind. This paper aims to provide an overview from a geotechnical standpoint of the main characteristics of the Italian seabed along the eastern coast. A database is built starting from the experience and data gained in the Italian Oil and Gas sector over the past decades, which comprises data related to cone penetration tests (CPT), soil characterization and results from laboratory tests. The database could be used as a tool to support geotechnical engineering applications for both design and installation purposes, facilitating the transfer of knowledge toward renewable resources.

Keywords: Offshore wind energy; Site characterization; Adriatic Sea.

1 INTRODUCTION

The Italian experience in the offshore sector dates back to the 1950s, with the first discoveries of gas fields in the Po Valley and oil reservoirs in Sicily, leading to exploration off the coasts of Ravenna and Gela to verify the extension of identified onshore deposits (Cazzini, 2018; Gottardi et al., 2020). Since then, over 100 marine platforms have been installed mainly along the western coast, in the North and Central Adriatic Sea (MASE, 2023).

Available geotechnical data relevant to the Italian Seas are still few and related to the oil and gas installations. The growing interest in the offshore renewable energy market in Italy (Pantaleo et al., 2005; Foti et al., 2010; Schweizer et al., 2016; Govoni et al., 2016; Travaglini et al., 2023; to cite a few) increases the need of available high-quality geotechnical data.

With this aim, RINA Consulting S.p.A. is developing an internal database based on the experience and data gained during geotechnical investigation campaigns and fieldwork carried out mainly during the 80s and 90s in the Adriatic Sea (Carpaneto et al., 1996; Paoletti et al., 2010). A first comprehensive elaboration is presented in this paper. The database could be valuable for early-stage feasibility studies and preliminary design phases for offshore installations and for a careful and sustainable planning of marine activities.

2 GEOLOGICAL AND GEOMORPHOLOGYCAL FEATURES

The Adriatic Sea is an epicontinental semi-enclosed basin elongated from the northwest to southeast direction. It can be divided into three different sections characterized by distinct bathymetric and morphologic settings: North, Central and Southern.

The Northern Adriatic Basin lies at the northern boundary of the Adria microplate which represents the foreland of the Southalpine, Dinaric and Apennine chains. It can be considered the submarine continuation of the Po basin over a continental shelf area. Here, most of the sediments are derived from erosion of the Alpine and Apennine chains by the Po River and, subordinately, by other rivers including the Adige, Brenta, and Reno. Currently, the Po River supplies most of the sediment, about 20 million tons per year (Colantoni et al., 1979).

The North Adriatic basin is generally referred to as the portion of the Adriatic Sea that extends from the Venetian lagoon at the northwest and Trieste coast at the northeast up to an imaginary line that connects the city of Ancona to Zadar in Croatia (Herak et al., 2005). This basin comprises the largest Mediterranean shelf with a maximum of 60 m of water depth in its south-eastern end. South of the Ancona–Zadar line extends the Central Adriatic Basin up to the Palagruža Sill, which ideally divides it from the South Adriatic Basin. It reaches 270 m of water depth in the Mid Adriatic Pit. South Adriatic Basin is characterized by the South Adriatic Pit that can extend up to 1200 m below the mean sea level. Further south, the basin connects to the Ionian Sea and the sea floor rises to 780 m.

Correggiari et al., (1996) showed a shallow geologic section, up to 70 m below the mudline, running southeast from the Po delta, at a distance from the shore of 205 km, where three main sedimentary phases of the late-Quaternary depositional sequence were identified moving towards the current seabed position. A Low Stand System Tract (LST) characterized by materials typical of alluvial deposits and delta front sand bodies comprising stiff clays and sands. The clays contain a significant silt fraction, typical of near-shore conditions. The sands are medium dense to dense and locally silty. A Transgressive System Tract (TST) characterized by Late Pleistocene to Holocene paralic deposits attributed to a lower delta plain environment. A High Stand System Tract (HST) that is the product of active Holocene to present sedimentation. The unit is a wedge-shaped body that thins seaward and is present along the coastal margin south of the Po Delta. The soils are typically normally consolidated plastic clays.

The Holocene sediment distribution in the Adriatic Sea exhibits a trend parallel to the coast. Holocene deposits are confined to a narrow zone along the western coast of the Adriatic (Trincardi et al., 1994).

3 SITE CHARACTERIZATION

The area investigated (Figure 3b) extends from south the Po delta down to south of Ancona and moves east towards the Croatian territorial waters in a zone that comprises the Northern Adriatic and the upper part of the Central Adriatic. Available meteorological and marine data indicate that the average annual wind speed at 100 m above the mean sea level at site is between 5.50-6.25 m/s, while, on the eastern central part, wind blows at a mean speed of 7.00 m/s, with a mean power density of around 500 W/m^2 (Global Wind Atlas, 2024). The area could potentially host wind farms. Local bathymetry ranges between 30-40 m below the mean sea level in the northern side and 60-80 m in the southern side, with a gradient of 50 m per 200 km.

3.1 Adriatic database

Data regarding geotechnical investigations and fieldwork for 51 different locations were collected in a database.

All fieldwork comprised boreholes with undisturbed sampling and in-situ testing. Undisturbed samples were typically preserved in waxed cartons while disturbed samples were placed in double plastic bags. All sample containers were labelled, placed in wooden crates and moved to a temperature-controlled storage. After demobilization samples were transported to the shore laboratory.

In situ testing regarded mainly Cone Penetration Tests (CPTs) performed in downhole mode. All tests used a 10 cm^2 piezocone with a maximum cone stroke of three meters and pushed at a rate of 2 cm/s. Investigated depths are those typical for traditional pile design, around 130 m below the mudline.

Laboratory tests were carried out according to ASTM standards. Testing programs included index, classification and physical properties tests, such as unit weight, sieve analysis, hydrometer, Atterberg limits, carbonate content, specific gravity and minimum and maximum dry density. Strength and compressibility testing included: unconsolidated undrained (UU), anisotropically consolidated undrained (CAU), isotropically consolidated drained (CID) triaxial tests, direct shear (DS) tests and load increment oedometer.

3.2 Geotechnical units’ description

Cone penetration test data and laboratory test results allowed to create a geotechnical model valid for deep and intermediate foundations. An example of a typical CPT profile in the investigated area is reported in Figure 1.

The large-scale geotechnical model developed for the investigated area can be discretised in three main geotechnical units with distinct characteristics.

The stratigraphic sequence is sealed by a thick layer of medium dense, fine sand (UNIT S1) is encountered. This unit shows a variable content of silts and sometimes very thin layers of peat and gas can be found. Description of gas and peat composition are out the scope of this contribute. The sands of this unit are siliceous and a have a significant content of feldspars and mica. Unit S1 is underlined by Unit F1, mainly composed by silts and silty clays.

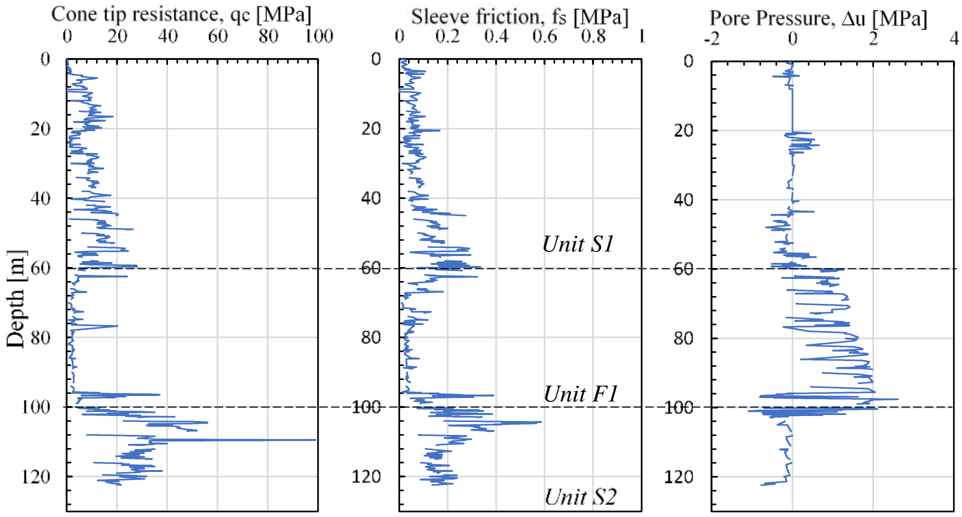


Figure 1. An example of CPTU data for the North Adriatic Sea.

Table 1. Summary of the database

UNIT	Top Boundary [a]	Bottom boundary [a]	SBT Classification [b]	USCS Classification [c]	n° in situ tests	n° Lab tests
S1	5-40 m	30-80 m	5-6	SP, SP-SM	33	267
F1	30-80 m	60-140 m	3-4	CL, CL-ML	33	541
S2	60-100 m	100-150 m	5-6	SP, SP-SM	20	32

[a] measured from the seabed. [b] from Robertson et al. (2015). [c] according to ASTM D2487-17e1

Due to a series of transgressions and emersions in the geological past, the soils of the unit are slightly overconsolidated. Below Unit F1, a layer of medium dense fine sand can be found (UNIT S2). In Table 1, the bottom and lower boundary of each unit is reported.

In the north of the investigated area, a thin layer of transgressive sand is found at the top of Unit S1. While, moving south, the transgressive sands are covered by a thin layer of very soft clay and silts. The geotechnical description of this superficial unit (average thickness of 2.5 m) requires an in-depth discussion that is out of the scope of the work.

3.2.1 Coarse-grained Units S1 and S2

Cone tip resistance (q_c) for the unit S1 reaches values up to 20 MPa in the Northern side and increases up to 30 MPa moving south. For unit S2, q_c ranges between 30-40 MPa. Relative density varied between 40-60% for unit S1, 60-80% for unit S2.

All sieve analyses present in the database were conducted in conformity with the ASTM D422-63 standard that was withdrawn in 2016, as there are no field campaigns after that date. In Figure 2 the grain size distribution curves referred to Unit S1 and Unit S2 are shown. Soil characteristic diameter, d_{50}, uniformity coefficient, C_u, coefficient of curvature, C_c, specific gravity, G_s, and minimum and maximum density are shown in Table 2, for unit S1 and S2 sands together with the corresponding standard used for the determinization.

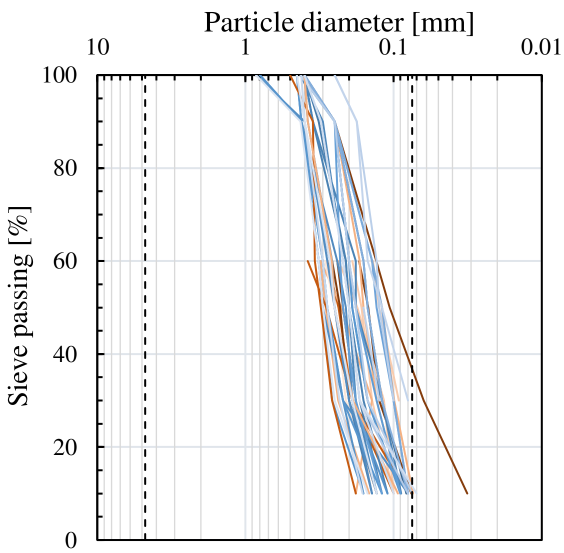


Figure 2. Grain size distribution curves for Unit S1 (blue scale) and S2 sands (orange scale).

Table 2. Adriatic sand characteristics

	d_{50} [1] [mm]	C_u [1] [-]	C_c [1] [-]	G_s [2] [-]	$\rho_{d,min}$ [3] $[kN/m^3]$	$\rho_{d,max}$ [3] $[kN/m^3]$
S1	0.20	2.16	1.23	2.71	12.69	15.31
S2	0.20	2.34	1.09	2.71	12.16	14.95

Note: Standard References: [1] ASTM D422-63. [2] ASTM D 854-06. [3] ASTM D4254-00, D4253-00

The average fines content for Unit S1 is $\bar{f}$=14.10% (σ=16.80%) when considering all the sieve analysis test results, while an average value of $\bar{\bar{f}}$=9.60% is obtained if outliners, i.e. values higher than $\bar{f} + 2\sigma$, are excluded (as suggested by DNGL-RP-C207, 2017). The majority of the test results fall in the 5÷10% range but a higher silt content is sometimes encountered especially in the Northern side and in the South-Eastern side of the unit. The average fines content for Unit S2 is $\bar{\bar{f}}$=8.90%, after removing outliners. The soil is classified as medium dense, fine, poorly graded sand sometimes silty sand, SP, SP-SM according to the Unified Soil Classification System (Table 1). Carbonate content varies between 5-15%.

Morphological analyses by optical microscopy were performed on retrieved samples only in more recent site investigation campaigns. Overall eleven morphological analyses are present in the database (eight for unit S1 and three for unit S2), ten of them were retrieved on the north-eastern side of the investigated area while one of them was on the southeast side.

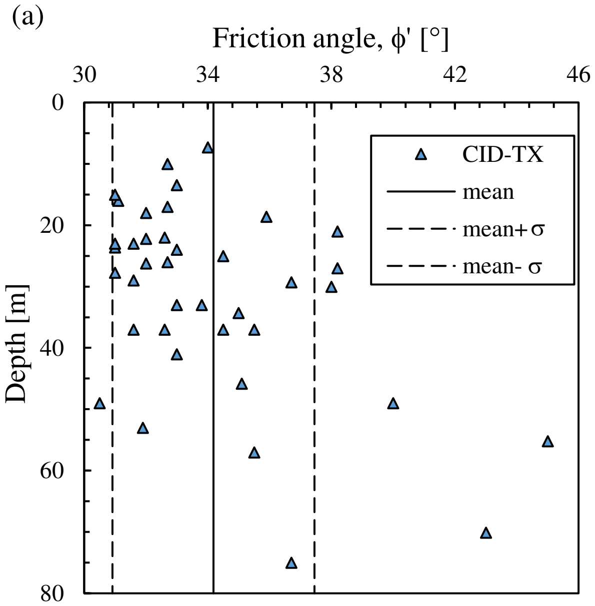
All tests agreed on the presence of subangular to sub-rounded siliciclastic (quartz and feldspars) and micaceous (muscovite and biotite) fine clasts with poor calcareous clasts. (Average contents: Quartz 71.3%, Feldspars 14.5%, Mica 8.1%, Carbonates 6.1%).

Isotropically consolidated drained triaxial tests were performed on dry samples for three levels of confining stresses. CID test results provided the effective friction angle φ' and effective cohesion intercept c' from Mohr diagrams. Figure 3 shows the vertical (3a) and spatial variation (3b) of the friction angles for unit S1. The average friction angle is 34.18°, with a standard deviation of 3.27°. Higher friction angles can be found at depths of 55 m and 70 m below the seabed in the southwest part of the analysed unit.

The average friction angle for Unit S2 was 31.04° with a standard deviation of 1.5° and it was almost uniform across the unit.

Spatial interpolation was performed using the built-in function provided in the open-source GIS software QGIS, (QGIS, 3.34.11) it allows for surface interpolation from vector point data by Inverse Distance Squared Weighting. The inverse distance weighting (IDW) approach is also known as inverse distance-based weighted interpolation.

It is the estimation of the value z at location x by a weighted mean of nearby observations. The inverse distance power parameter β determines the degree to which nearer points are preferred over more distant points (Hartmann et al., 2023). Twelve interpolation points were used with a default value of two for the power parameter.



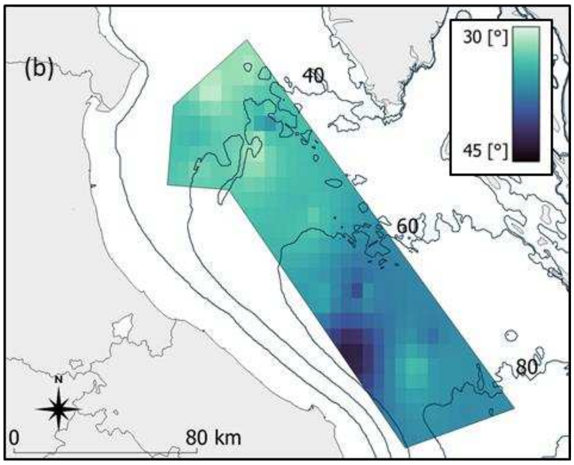


Figure 3. Friction angles from CID triaxial tests for unit S1. a) Variation with depth, the mean value is reported in a black solid line while standard deviation in black dashed lines. b) Spatial interpolated values processed in QGIS (QGIS, 3.34.11)

Output raster cell dimensions were calibrated to balance the need for a smoother transition from cell to cell and the necessity of keeping the number of generated cells sufficiently low to avoid an increment in the generated error. The input data vector was divided into two sub-vectors, a "train" and a "test" vector. Values from the original input vector were randomly assigned to each of the sub-vectors using the random selection tool provided in QGIS. Surface interpolation was performed on the "train" sub-vector while raster output surface values were compared to the "test" sub-vector, with an average error of around

7%, to assess consistency in the generated output using the cross-validation method (Stone, 1974).

3.2.2 Fine-grained unit F1

Unit F1 is composed by low to medium plasticity silty clay (CL, CL-ML) according to the Unified Soil Classification System (Table 1). Sieve analyses on retrieved samples confirmed an almost 95% of fines content with a composition of 70%-75% silts and 20%-25% of clay.

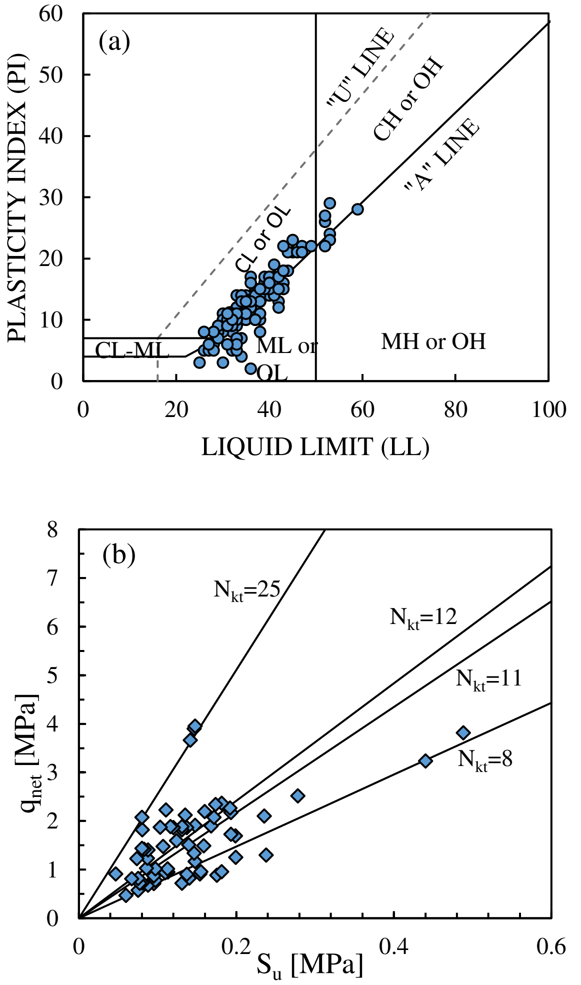


Figure 4. a) Casagrande plasticity chart for unit F1. b) Relation between S_u from lab tests and q_{net} from CPT with esteem of mean, median, 5th and 95th percentiles for N_{kt}.

Atterberg limits analyses and determination of the natural water content showed that Unit F1 fines have an average Plasticity Index (PI) of 12.98% (σ=5.18%, COV=0.4) and average water content ($\overline{w}$) of 27.9% (σ=5.75%, COV=0.2). Plasticity varies between 8-18% across the unit, but higher PI values (PI=20-30%) can be found towards the centre of the unit F1. All the samples fall upon the “A line” in the Casagrande plasticity chart. (Figure 4a). Cone tip resistance of the clay unit was lower than 8 MPa. The unit is composed of normally consolidated silty clay, sometimes slightly over-consolidated (OCR <5). The Overconsolidation ratio, OCR, was evaluated using Kulhaway and Mayne (1990) to compute the preconsolidation ratio as: $\sigma'_p=0.33(q_c-\sigma_v)^n$ where n=1 for clays. Values obtained were compared to the results of the few oedometric tests present in the database.

Consolidated undrained and unconsolidated undrained triaxial testes allowed for the calibration of the cone bearing factor N_{kt}. When comparing the results from the two triaxial tests, undrained shear strength from UU tests were multiplied by a factor of 1.2 in order to be compared to CAU results as suggested by DNVGL-RP-C207. The laboratory results were compared to the net cone tip resistance ($q_{net} = q_t - \sigma_{v0}$) from CPT measurements on corresponding locations and depth (Figure 4b). The mean N_{kt} value was 12, while the median, 5th and 95th percentiles were of 11, 8, 25 respectively. Carbonate content spanned in the range from 5 to 30%.

Closer to shore fines deposits exhibited a higher content of sand, sometimes layers of sand thicker than 50 cm were encountered. The soil deposit is characterized by low to medium plasticity silty clay and high plasticity fat clays, CL-CH according to the Unified Soil Classification System, with a mean water content of $\overline{w}$=29.6%. In this zone a higher carbonate content is registered (15-30%) compared to the rest of the unit.

4 CONCLUDING REMARKS

The paper presents a preliminary geotechnical site characterization of the Italian seabed along the eastern coast based on data collected in a database currently being developed by RINA Consulting S.p.A.

The investigated area has the potential for hosting wind farms. Local bathymetry allows for multiple engineering solutions for supporting wind turbines, in particular, monopiles and jackets on either piles or suction caissons can be suitably installed at site. Water depths in the south-eastern side could allow for the installation of tension leg platforms (TLP) or semisubmersibles moored to the seabed.

Typical monopiles and piles for supporting wind turbines have embedment lengths that could be entirely installed in the first unit of sand S1, which extends up to 80 m below the seabed.

Laboratory and in situ tests allowed for a comprehensive description of this unit. Based on the dataset elaboration results, up-to-date design methods, such as the recently proposed unified CPT method for assessing the axial capacity of piles (Lehane et al.,

2020) or the PISA framework for assessing monopiles lateral capacity, can be suitably applied (Byrne, 2020).

Even though no critical issues arose from the analysis, some particular design aspects should be wisely evaluated: liquefaction risk potential should be assessed due to the seismicity of the zone and installation by suction should be carefully designed, since the presence of fines content may reduce soil permeability preventing the foundation to reach the required installation depth. Furthermore, in coarse-grain soil the instauration of a critical hydraulic gradient may determine the failure due to piping.

AUTHOR CONTRIBUTION STATEMENT

G. Orlando: Data curation, Formal Analysis, Writing. Software. **N. Pontani**: Formal Analysis, Conceptualization, Methodology, Supervision. **F. Panico**: Visualization, Supervision. **L. Govoni**: Founding, Reviewing and Editing, **A. Murianni**: Visualization, Reviewing.

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