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A multidisciplinary tool for the development of a regional-scale geotechnical model: a case study in the North-Western Adriatic coastal area

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Abstract

The paper describes the geotechnical model of a coastal flat area facing the Adriatic Sea, between the municipalities of Cesenatico and Bellaria-Igea Marina (Emilia-Romagna region, Italy). On the basis of a large experimental database provided by the Geological, Seismic and Soil Survey of the Emilia-Romagna Authority, a stratigraphic scheme of the upper 40 m of this coastal plain subsoil has been defined and reliable estimates of parameters for the different soil units have been derived. The accurate mechanical characterization of soils, also reflecting their sedimentological framework, allows the development of a regional-scale geotechnical model providing a reliable and useful support to geotechnical engineers working in this area or similar geological environments.

Peer-review under the responsibility of the organizing and scientific committees of CNRIG2016

Keywords: quaternary sedimentology; geological model; geotechnical model; coastal deposits; Adriatic coast

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1. Introduction

This paper presents a joint study carried out by researchers of the University of Bologna in cooperation with experts

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of the Geological, Seismic and Soil Survey (GSSS) of the Emilia-Romagna Authority (RER), for the development of a regional-scale geological and geotechnical model of the coastal plain facing the Adriatic Sea, in the south-eastern margin of the Emilia-Romagna Region. This area, approximately 12 km long and 10 km wide, includes the municipalities of Cesenatico, Gatteo, San Mauro Pascoli, Savignano sul Rubicone and Bellaria-Igea Marina. It is a well-known, heavily urbanized touristic site in Italy, very famous for its wide sandy beaches.

The information provided by a large experimental database, consisting of boreholes (BH) and piezocone tests (CPTU) uniformly distributed in the investigated area as well as of a few laboratory tests, coupled with details on the recent sedimentary evolution of the shallow subsurface, allowed a detailed reconstruction of the stratigraphic architecture and the geotechnical characterization of sedimentary bodies, thus resulting in a useful tool for engineering planning or for preliminary geotechnical design.

Nomenclature

f_s	friction sleeve
N_{kt}	cone factor
q_t	corrected cone resistance
$q_{t,net}$	net (or effective) cone resistance (q_t - σ_{v0})
u_0	hydrostatic pore water pressure
u	pore water pressure
σ_{v0}	total vertical stress
σ'_{v0}	effective vertical stress
B_q	pore pressure parameter, $(u - u_0)/(q_t - \sigma_{v0})$
F_r	normalized friction ratio, $100 \cdot f_s/(q_t - \sigma_{v0})$
Q_{tn}	normalized cone resistance, $\{(q_t - \sigma_{v0})/p_a\} \cdot (p_a/\sigma'_{v0})^n$, with $n \leq 1$ and $p_a = 0.1013$ MPa
I_{cn}	$[(3.47 - \log Q_{tn})^2 + (\log F_r + 1.22)^2]^{0.5}$

2. Geological settings

The geographical boundaries of the study area, together with the location of site investigations and the alignments selected for the stratigraphic cross sections are shown in Figure 1. From a geological point of view, the area is almost entirely characterized by the so-called *Emilia Romagna Supersynthem* (*Supersintema Emiliano-Romagnolo*, in Italian) which basically consists of an alternation of alluvial, deltaic, coastal and marine deposits corresponding to different order depositional cycles. Their thickness is maximum near the coast and progressively diminishes towards the Apennines.

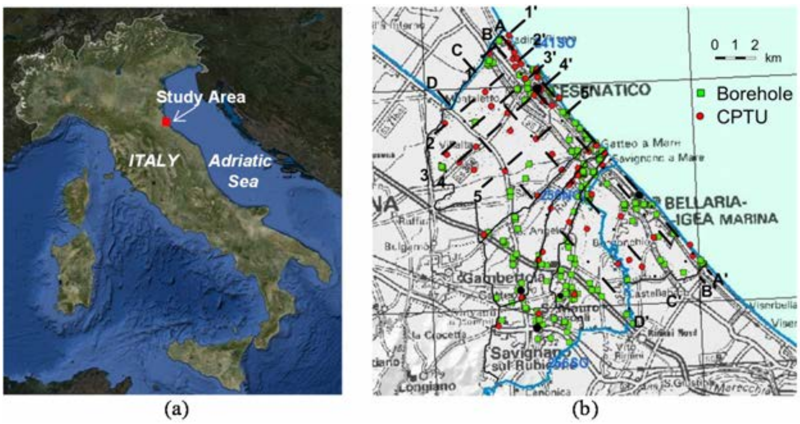

Fig. 1. (a) Location of the study area; (b) Geographical distribution of site investigations and cross sections analyzed

In particular, the *Emilia-Romagna Supersynthem* is subdivided into two lower-rank units, namely the *Lower Emilia-Romagna Synthem* and the more recent *Upper Emilia-Romagna Synthem* (AES), which dates back to Middle Pleistocene. This latter consists of a number of subsynthems (AES_4 to AES_8), among which the Holocene *Ravenna Subsynthem* (AES_8) includes most of the deposits analysed in this study.

Focusing our attention on the area under investigation, it must be emphasized that the stratigraphy along the coast differs from the depositional architecture typical of the inland plain. Indeed, in this latter area AES_8 mainly consists of clays, silts, alternate silts-silty sands as well as sand lenses, referable to floodplain, overbank or fluvial channel deposits. Below, organic-rich dark clays, interpreted as paludal deposits, together with highly fossiliferous lagoonal silts to coastal sands are present.

Along the coastline, a shallow sand wedge, due to post-glacial transgression-regression of the sea, defines a thin littoral strip, 0.5 to 1 km wide. Here, the depositional sequence is characterized by a sharp and erosional boundary between alluvial and littoral facies.

3. Methodology

The experimental database was entirely provided by the GSSS. Site investigations included a total of 140 BH logs, 52 CPTU and 5 seismic piezocone tests (SCPTU), all generally pushed to a depth between 15 and 30 m. In addition, laboratory tests for soil classification purposes as well as for the evaluation of the basic mechanical parameters were carried out on approximately 15% of the available BHs.

The geotechnical model mainly relied on CPTU tests and BH logs. The information obtained from laboratory tests were also taken into account to aid in the interpretation. As a first step, the data from CPTU tests were used to define the soil stratigraphy. Given the large number of BH logs, the CPTU-based soil profile was then cross-checked with the soil column provided by a BH located nearby. In this way, a limited number of soil units could be identified and the most significant geotechnical parameters, describing stress history, compressibility and shear resistance, were calculated for each soil layer, adopting a statistical interpretation of the data.

In particular, the soil stratigraphy was determined using the rather popular and recently revised CPTU-based classification framework developed by Robertson [1]. According to this approach, soil classes are defined in terms of the *Soil Behaviour Type* (SBT_n), corresponding to a well-defined interval of values assumed by the *Soil Behaviour Type index*, I_{cn}. This latter is iteratively calculated from the dimensionless normalized cone resistance Q_{tn} and the friction ratio F_r, according to the procedure described in [1]. In fine-grained soils, where excess pore pressures develop during cone penetration, the values assumed by B_q were carefully examined to aid in soil classification. Figure 2 shows a representative example of CPTU data, together with soil classification results in terms of I_{cn} and SBT_n. Soil stratigraphy from an adjacent BH is also plotted in the figure and the interpretation of data in terms of a limited number of soil units (labelled as *A, B, D*) is proposed.

Effective shear resistance of granular soils, expressed in terms of the peak friction angle ϕ'_p, was calculated using the well-established correlation proposed by Kulhawy and Mayne [2], which has proved to be an excellent predictor in evaluating the drained strength of clean to slightly dirty sands of quartz, feldspar or other rock mineralogy. It is worth emphasizing that marine sands, such as those investigated in this study, may contain carbonate minerals due to the presence of shell fragments. However, Rocchi et al. [3] have shown that the soil grading plays a more important role than that of the mineralogy or particle shape. Lunne et al. [4] also stated that soils with carbonate content of less than 50% - 70% tend to behave in a similar manner to non-calcareous soils.

In fine grained soils, ϕ' was determined according to the correlation of Mayne and Campanella [5], based on the stress normalized cone resistance Q_t (obtained from Q_{tn}, assuming n =1) and the pore pressure parameter B_q. Such approach is applicable when soil exhibits a contractive response, in particular when $0.1 < B_q < 1.0$. For these sediments, the undrained shear resistance s_u was determined as well, by assuming a cone factor $N_{kt} = 20$ to convert the CPTU net cone resistance $q_{t,net}$ to undrained strength. Such rather conservative value was settled also taking into account typical estimates of *OCR* obtained from CPTU interpretation, generally in the range 2-4.

Finally, the compressibility characteristics of soils were described in terms of the one-dimensional constrained modulus M. In coarse-grained soils, this parameter was calculated using the well-established correlation proposed for sands by Lunne and Christophersen [6], whilst the approach of Kulhawy and Mayne [2] was adopted in clays.

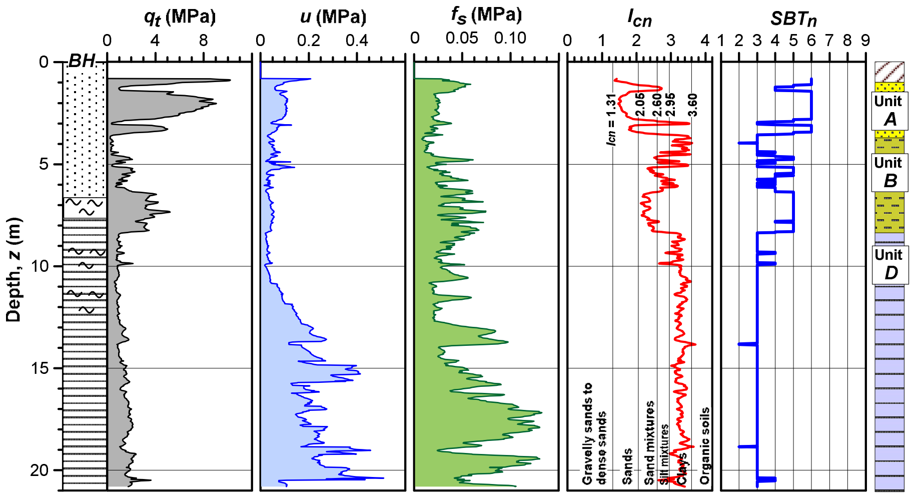

Fig. 2. Example of the analysis of a CPTU to identify the soil stratigraphy.

Particular attention was paid to the geotechnical characterization of intermediate sediments (i.e. silts and silt mixtures), where partial drainage conditions are very likely to occur during cone penetration [7]. In this case, the application of well-known and widely accepted interpretation approaches, developed either for sands or clays, must be treated with a great deal of uncertainty.

4. Geotechnical model

To build the geotechnical model of the area, a number of representative sections, either drawn parallel to the coastline or perpendicular to it, where identified and first separately analysed. Details on the selected cross sections, in terms of length, direction, number of BH and CPTU involved in each alignment, are reported in Table 1. The longitudinal NW-SE sections, labelled as *A-A′* to *D-D′*, cut across the whole area, whereas the cross sections *1-1′* to *6-6′* are mostly located in the northern part of the territory. The geotechnical model is here described with reference to only two perpendicular alignments, namely sections *C-C′* and *3-3′*, which are shown in Figure 3.

In cross section *3-3′*, close to the coastline, a well-defined top layer of sand (*Unit A*), approximately 5 m thick, can be recognized. This soil unit, referable to the recent littoral sand deposits, is at times followed by sand mixtures (fine sands, silty sands and sandy silts) which are identified as *Unit B*. An example of a similar stratigraphic setting is provided in Figure 2. Moving inland, the shallow deposits mainly consist of silts (*Unit C*), having a variable thickness along the alignment (5 to 8 m). Such units are all referable to AES_8.

Table 1. Selected sections

Cross-section	Length (km)	Direction	Distance from coastline (km)	No. CPTu	No. BH
A-A'	15.18	NW-SE	0.25	12	17
B-B'	14.66	NW-SE	0.67	8	2
C-C'	9.06	NW-SE	2.13	10	6
D-D'	10.26	NW-SE	4.11	7	1
1-1'	1.36	NE-SW	-	2	1
2-2'	4.12	NE-SW	-	4	-
3-3'	6.80	NE-SW	-	4	2
4-4'	6.62	NE-SW	-	3	-
5-5'	5.56	NE-SW	-	2	1

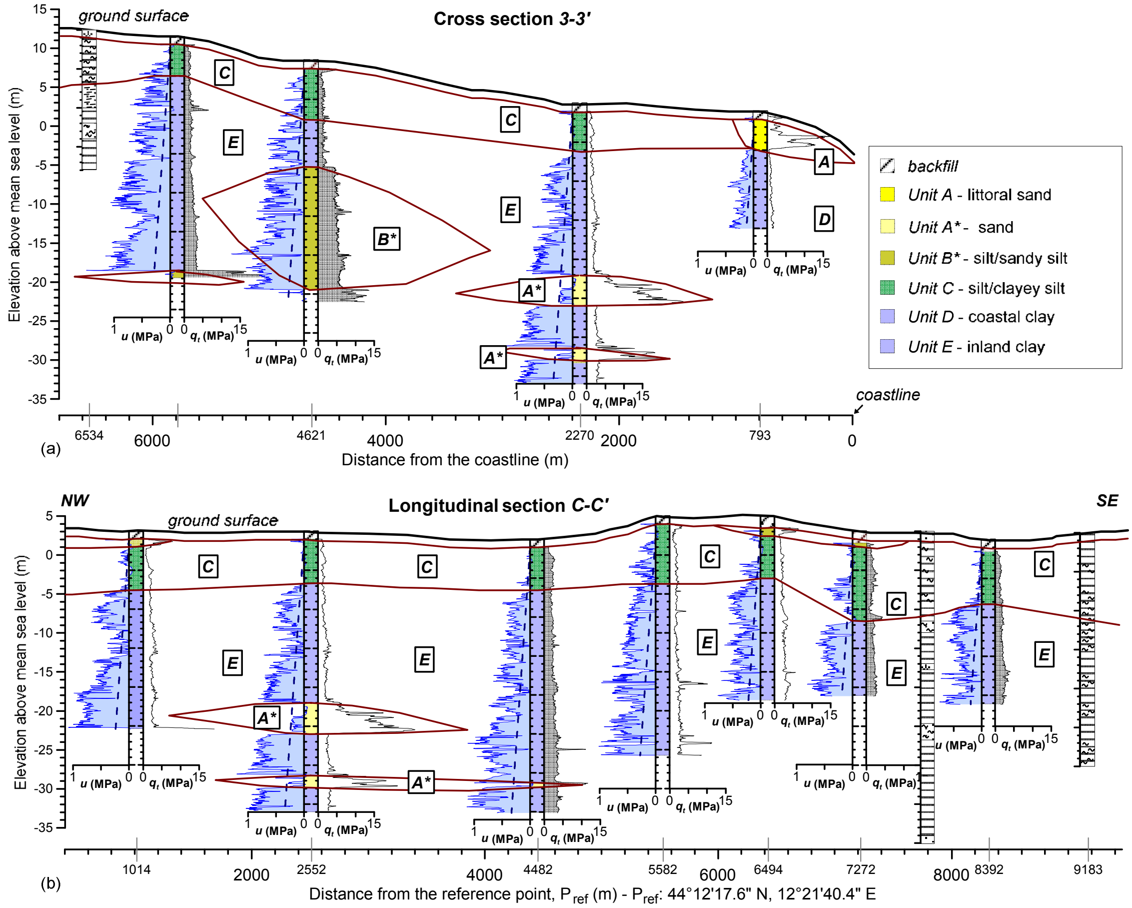

Fig. 3. Representative stratigraphic sections, (a) perpendicular and (b) parallel to the coastline

Below units *A* and *C*, a rather homogeneous clay unit is generally detected, down to 30-35 m in depth. Its lower boundary is likely to be part of AES_7. A few thick lenses of dilative fine sands (*A**) and contractive silt mixtures (*B**) are occasionally found within such unit. Clays exhibit higher consistency moving inland, perhaps due to the presence of interbedded silty and sandy layers. Accordingly, two different clay units have been distinguished, i.e. *Unit D* close to coastline and *Unit E* inland.

By considering the entire amount of data collected in the area, similar stratigraphic conditions were identified in the other alignments. The mechanical parameters of the soil units were first estimated at a single CPTU test level; the values obtained from the whole cone sounding database were then analyzed in order to identify the most reliable sets of soil parameters to be assumed for the different stratigraphic units. The box–whisker graph shown in Figure 4 aims at providing a better insight into the computed estimates of the mechanical properties of the main soil units (i.e. *A*, *B*, *C*, *D*, *E*), by displaying the median, the lower and upper quartiles, the maximum and the minimum values of φ', s_u, M.

As regards *Unit E*, the variability of predictions for φ', s_u, M has been analyzed at a single test level, at the cross section level (*3-3′*) and, finally, at the regional scale. The plots clearly shows that the median of the different soil parameters does not differ significantly when the analysis is extended to the whole area. Furthermore, it is worth observing that units *D* and *E*, though both referable to clay-like soils, exhibit significantly different values of the effective shear resistance φ', of the undrained strength s_u as well as of the constrained modulus M, thus suggesting higher consistency for the clay inland. These results are consistent with estimates of *OCR*, which were found to be higher for *Unit E*, typically from 2 to 3.7.

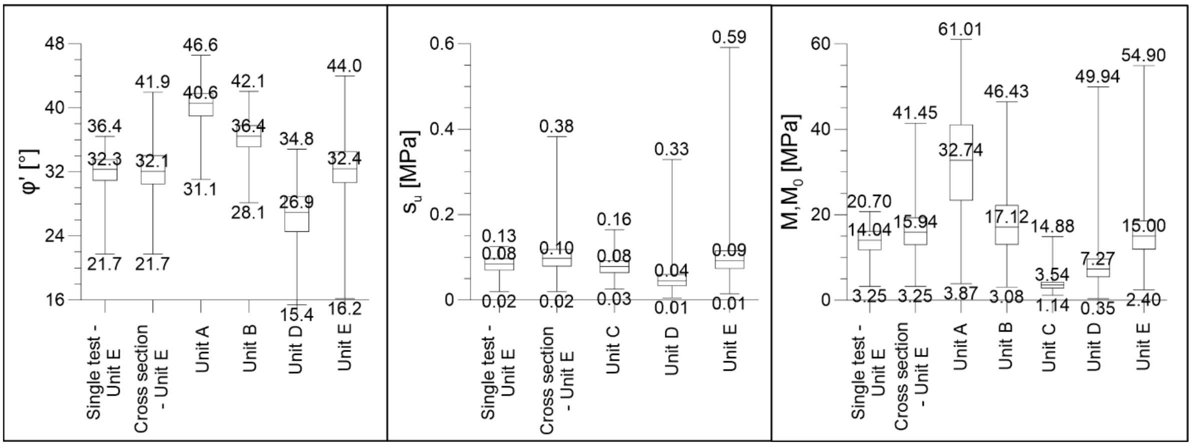

Fig. 4. Variability of the soil parameters for the different stratigraphic units: (a) φ', (b) s_u and (c) *M*.

With regard to the predominantly silty *Unit C*, reliable estimates of φ', valid for the whole area, were difficult to obtain, due the impossibility of applying the method of Mayne and Campanella [5] to most of the relevant CPTU data. Besides, the significantly low estimate of *M* in this unit needs further investigation and consideration, thus confirming complexity and uncertainties in geotechnical characterization of intermediate soils [8].

Finally, it is worth observing that *M* generally shows the highest variability within the different units.

5. Conclusions

The paper describes part of the study carried out to develop a geotechnical model for a coastal area of the Emilia-Romagna region, between the municipalities of Cesenatico and Bellaria-Igea Marina, over an area approximately 10 km long and 12 km wide. On the basis of a large experimental database, including both in situ and laboratory tests provided by the Geological, Seismic and Soil Survey Department of the Emilia-Romagna Authority, a few stratigraphic soil units have been identified and reliable estimates of the main mechanical properties have been obtained. By performing an accurate geotechnical characterization of the soil units, also reflecting their sedimentological environment, the study aims to provide some useful preliminary information to geotechnical engineers working in this area or similar geological environments, not only in terms of representative values of soil parameters but also with regard to the selection of appropriate geotechnical investigation tests and to issues peculiar to the data interpretation.

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