Proceedings of the XVII ECSMGE-2019
Geotechnical Engineering foundation of the future
ISBN 978-9935-9436-1-3

doi: 10.32075/17ECSMGE-2019-0455

XVII European Conference
ECSMGE 2019
Reykjavik
on Soil Mechanics
and Geotechnical Engineering

Developing a regional-scale geotechnical model of the north-western Adriatic coastal area (Italy) for urban planning and robust geotechnical design

Développement d'un modèle géotechnique à échelle régionale de la côte Adriatique nord-ouest (Italie) pour la planification urbaine et pour un solide projet géotechnique

L. Tonni
DICAM, University of Bologna, Bologna, Italy

M.F. García Martínez, D. Maurini
DICAM, University of Bologna, Bologna, Italy

L. Calabrese
Geological, Seismic and Soil Survey of the Emilia-Romagna Authority, Bologna, Italy

ABSTRACT: The paper presents a study for the development of a regional-scale geotechnical model of the coastal plain facing the Adriatic Sea, in the south-eastern margin of the Emilia-Romagna Region (Italy). This area 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 and piezocone tests, coupled with details on the recent sedimentary evolution of the shallow subsurface, was used to develop a stratigraphic model of the upper 30m subsoil and to obtain a geotechnical characterization of the different soil units. Such accurate geotechnical characterization may be useful to geotechnical engineers working in this area or similar geological environments, in terms of representative values of soil parameters, guidelines for better design of geotechnical investigations, identification of issues peculiar to data interpretation and recognition of potential geotechnical problems. A similar study may result in a useful tool for urban planning and robust geotechnical design.

RÉSUMÉ: Cet article présente une étude pour le développement d'un modèle géotechnique à l'échelle régionale de la plaine côtière face à la mer Adriatique, au sud-est de la région Emilia-Romagna (Italie). Il s'agit d'un site touristique très connu et urbanisé, réputé pour ses vastes plages. Les informations obtenues à partir d'une grande base de données composée de forages et d'essais de pénétration statique (piézocône), associées aux informations sur l'évolution sédimentaire du site, ont été utilisées afin de développer un modèle stratigraphique du sous-sol jusqu'à 30 m de profondeur et d'obtenir une caractérisation géotechnique des différentes unités de sol. Cette étude peut être très utile aux ingénieurs travaillant dans cette zone ou autres environnements géologiques similaires, afin de identifier des valeurs représentatives des paramètres du sol, des lignes directrices pour la sélection et la programmation des investigations géotechniques ainsi que pour l'identification de problèmes dans l'interprétation des données ou de probables risques géotechniques. L'étude proposée peut donc représenter une base pour la planification urbaine et une robuste conception de projet géotechnique.

Keywords: Quaternary deposits; coastal deposits; geotechnical model; cone penetration test; Adriatic coast

1 INTRODUCTION

This paper presents a few results from a joint study carried out by researchers of the University of Bologna in cooperation with experts of the Geological, Seismic and Soil Survey (GSSS) of the Emilia-Romagna Authority (RER), for the development of a regional-scale geotechnical model of the coastal plain facing the Adriatic Sea (Figure 1), in the south-eastern margin of the Emilia-Romagna Region (Italy). The investigated territory, approximately 12 km long and 10 km wide, is a heavily urbanized and renowned touristic area, very famous for its wide sandy beaches.

The socio-economic significance of this region and the intense anthropogenic pressure exerted by human activities have stimulated over the last years an increasing demand for a sound understanding of the recent sedimentary evolution as well as for a proper geotechnical characterization of the shallow sediments of this area, which might help in identifying potential geotechnical issues (e.g. ground settlements or stability) as well as effective strategies for engineering design, risk assessment and urban planning.

Figure 1. Location of the study area.

The study proposed herein uses a dataset of borehole (BH) logs and piezocone (CPTU) measurements uniformly distributed throughout the investigated area, coupled with information on the depositional environment of the upper 30 m sediments, in order to obtain a detailed reconstruction of the stratigraphic architecture and the geotechnical characterization of the different sedimentary bodies. A few issues on the estimate of soil parameters from in-situ testing, especially in the so-called "intermediate" sediments, and potential risk related to ground settlements in fine-grained soils or liquefaction phenomena in sandy layers are discussed.

The idea behind the study is basically to provide a baseline for design and interpretation of site investigations in future civil engineering projects as well as a useful decision support tool for urban planning. The geotechnical model presented herein is a development of a preliminary 2D model described in Tonni et al. (2016). Examples of similar large-scale geotechnical models, also accounting for the sedimentological framework, have been proposed for different depositional environments worldwide by Delgado et al. (2003), Dipova (2011), Ferrario et al. (2015) among others.

2 GEOLOGICAL SETTING

The geographical boundaries of the study area, together with the location of site investigations forming the main part of the available georeferenced database, are shown in Figure 2. The traces of the 11 alignments selected for interpretation, drawn either parallel (*A-A'* to *E-E'*) or perpendicular (*1-1'* to *6-6'*) to the shoreline, have been also reported in the Figure.

Such area is part of the Emilia-Romagna coastal plain, which is the seaward portion of the wider Po basin. Sediments of this area are referable to a Late Quaternary depositional sequence known as the *Emilia-Romagna Supersynthem*, consisting in an alternation of alluvial, deltaic, coastal and marine deposits

arranged into different sedimentary cycles driven by transgression-regression of the sea.

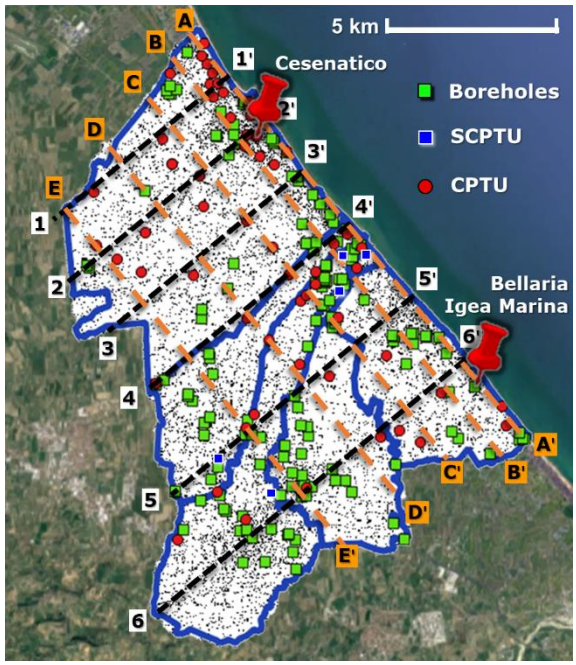

Figure 2. Area of study with the location of site investigations and selected alignments for the cross sections.

In particular, the Supersynthem is subdivided into two lower-rank hierarchic units, namely the *Lower Emilia-Romagna Synthem* (*AEI*, Middle Pleistocene) and the more recent *Upper Emilia-Romagna Synthem* (*AES*, Middle to Upper Pleistocene and Holocene), the latter consisting of alluvial fan and alluvial plain alternations in marginal areas, grading basinward into cyclic alternations of alluvial and deltaic/shallow-marine deposits (Amorosi et al., 2004). The *AES* is further subdivided into lower rank depositional cycles, typically referred to as subsynthems, with the *AES8* (the *Ravenna Subsynthem*) being the one relevant to this study.

This geological unit, dating back to the beginning of the Holocene (approx. 12,000 years ago), mainly consists of littoral sands, forming a sort of belt or wedge-shaped coastal sand body, 0.5 to 1 km wide and 4 to 12 m thick, and alluvial sediments deposited by Apennine rivers. The alluvial sequences can be in turn distinguished between fluvial channel deposits, floodplain deposits and levee and crevasse deposits. The *AES8* does not present here any depositional nor erosional gap, except close to the coastline, where the littoral sands are separated from alluvial sediments by an erosional marine scarp formed by the high stand of the sea level during the last postglacial optimum. Floodplain deposits, composed of fine-grained sediments, form a wedge up to 20 m thick, with locally interbedded clays containing undecomposed organic material.

Figure 3 shows the cyclic facies architecture of the upper 40 m beneath the study area, with respect to the cross-section *T-T'* (Fig. 3b) and the longitudinal section *L-L'* (Fig. 3c).

3 THE REFERENCE DATABASE AND THE STRATIGRAPHIC SCHEME

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. A few laboratory tests for soil classification purposes were made available for interpretation as well, together with a limited number of tests for the evaluation of the basic mechanical soil parameters.

The proposed geotechnical model mainly relies on the interpretation of CPTU tests and BH logs. Laboratory tests results have been used, whenever possible, to aid in field measurement interpretation. Figure 4 shows the log profiles of a representative piezocone test (516X) located very close to the coastline, between the alignments *2-2'* and *3-3'*. Soil classification results, in terms of Soil Behaviour Type Index I_{cn} and the corresponding Soil Behaviour Type SBT_n (Robertson, 2009), have been reported as well, together with the soil classes predicted by the method proposed by Schneider et al. (2008).

The SBT_n profile reveals a well-defined top layer of sand (*Unit A*), approximately 9.5 m thick,

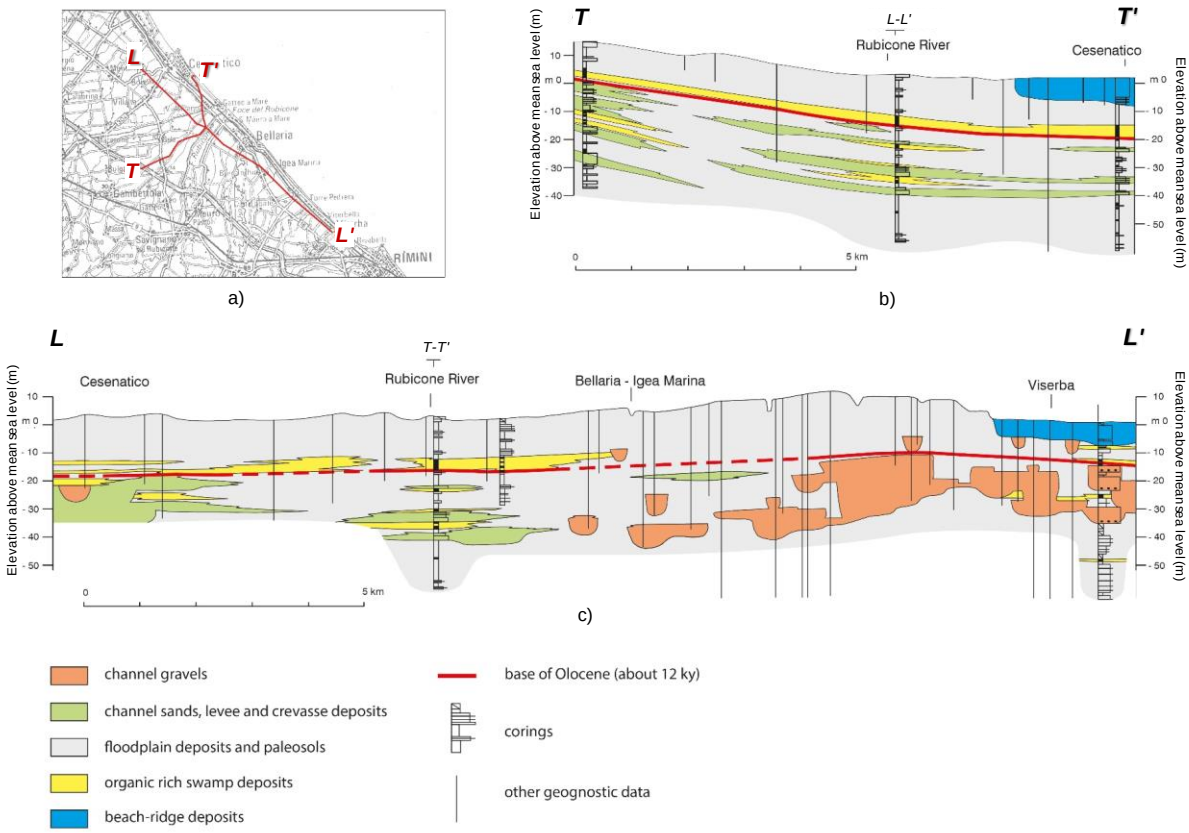

Figure 3. Late Quaternary stratigraphic architecture beneath the Adriatic coastal plain from Cesenatico to Viserba, along cross-sections T-T'(b) and L-L'(c). Section traces are drawn in (a).
Modified from Carta Geologica d'Italia 1:50000 Foglio 256 "Rimini", 2005 – APAT Servizio Geologico d'Italia – Regione Emilia-Romagna.

corresponding to the beach-ridge deposit. This soil unit exhibits a fining-downward trend, with fine silty sands being prevalent from 7 m in depth to the lower boundary. Below, the Robertson's (2009) approach predicts a clear predominance of clayey sediments (SBT_n = 3, only occasionally SBT_n = 4), whereas the Schneider et al. (2008) method details a dense alternation of silts/clays with low rigidity index (I_r) and transitional soils, the latter denoting a large variety of mixed soil types potentially affected by partial drainage phenomena during cone penetration tests.

Such predominantly fine sediments (*Unit B2*) form a 20 m thick layer referable to a floodplain depositional environment, whilst the interbedded alternation of sands and silty sands detected at 25-27 m in depth may be interpreted as a levee/crevasse deposit (*Unit LC*).

Moving inland, the upper 35 m are almost entirely composed of fine-grained sediments of floodplain environment, either with a prevalence of clays (and thus labelled as *Unit B2*) or, alternatively, of silts and clayey silts (*Unit B3*). As an example of typical piezocone log profiles for non-coastal tests, results from CPTU 509, located on the cross-section *4-4'* at approximately 4 km from the coastline, are shown in Figure 5. Interbedded silty sands, having a somewhat internal fining upward trend and referable to a fluvial channel environment (*Unit B1*), or dense

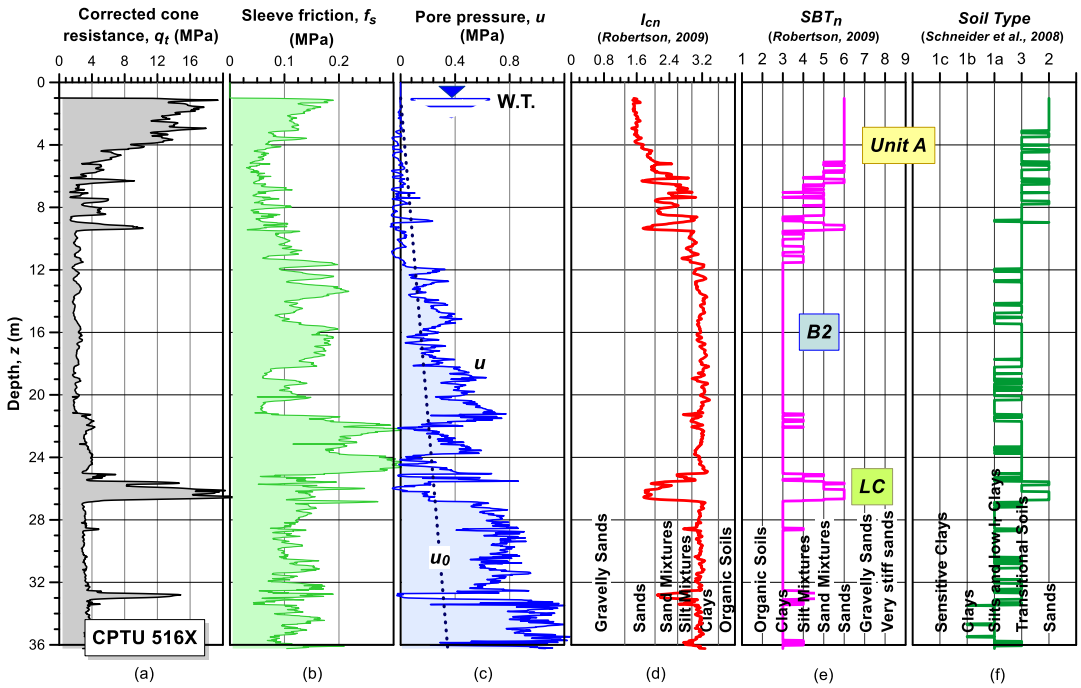

Figure 4. Profiles of a representative CPTU located close to the coastline (a-c) and CPTU-based classification results (d-f).

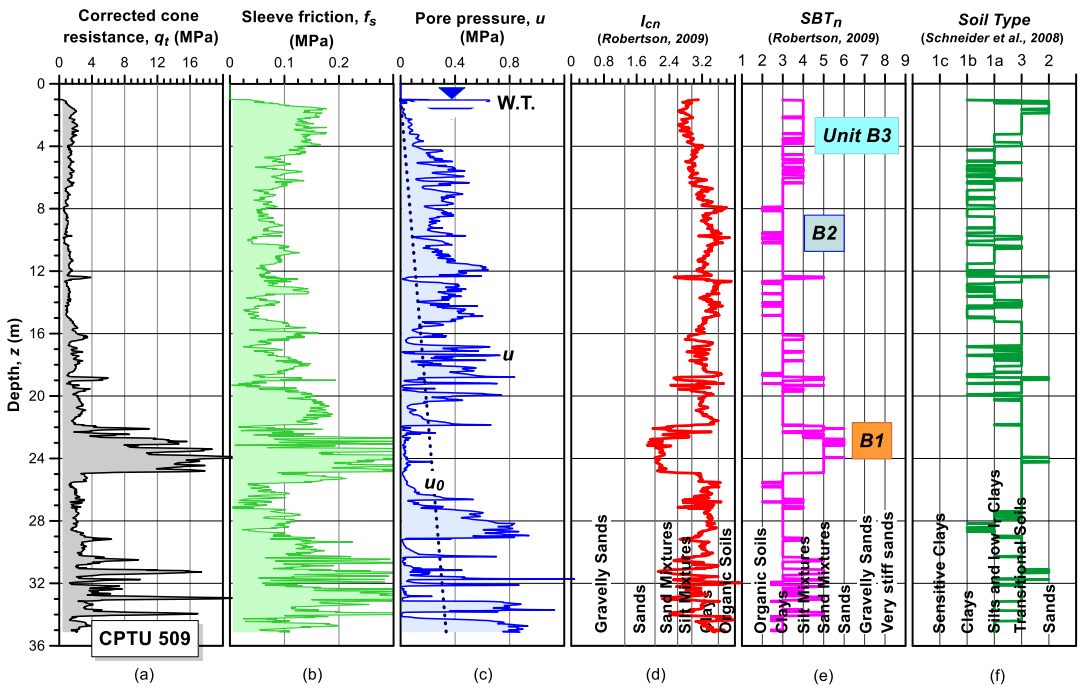

Figure 5. Profiles of a representative CPTU located inland (a-c) and CPTU-based classification results (d-f).

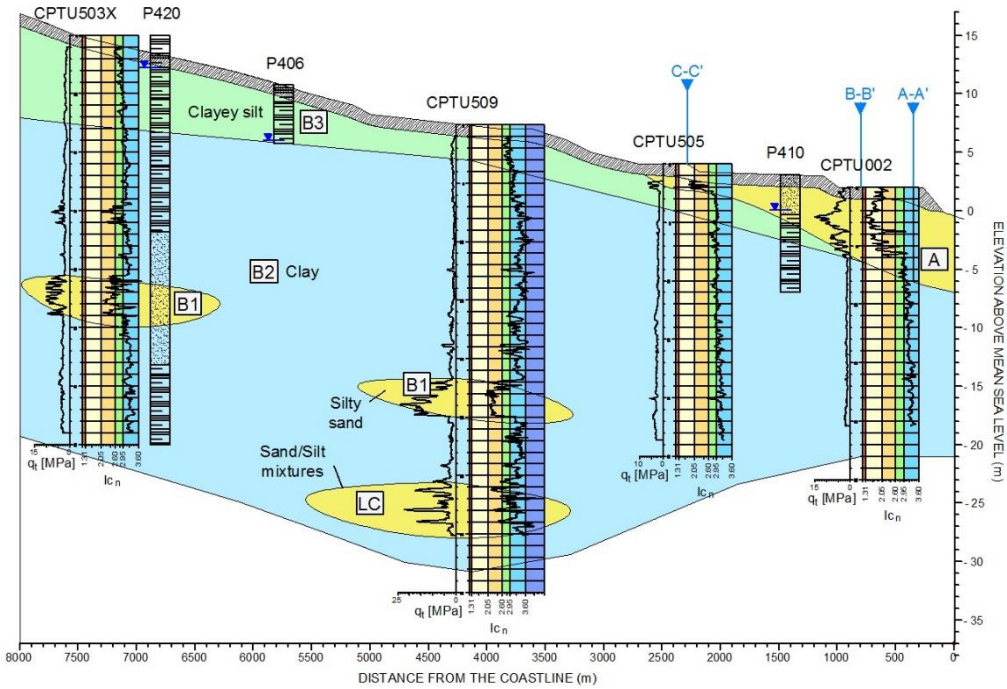

Figure 6. Geotechnical stratigraphic scheme of section 4-4'.

alternations of sand mixtures, silts and clays (*Unit LC*) are occasionally detected from 22 to 36 m in depth.

Figure 6 provides the geotechnical stratigraphic scheme obtained from interpretation of a number of boreholes and CPTU tests located on the alignment *4-4'* (Fig.2), perpendicular to the coastline. For each geotechnical soil unit, the corresponding interpretation in terms of sedimentary facies has been also reported. A similar stratigraphic arrangement has been also identified for all the cross-sections parallel to *4-4'*, as confirmed by the 3D scheme in Figure 7.

4 THE SOIL CHARACTERIZATION

The geotechnical characterization of the different soil units has been initially carried out at a single CPTU test level and then compared with intepretation of adjacent tests, in order to determine the most reliable set of soil parameters for each stratigraphic unit and possibly identify their spatial variability.

As regards the shear strength of the beach-ridge sands, the upper 5 m of *Unit A* are characterized by a mean value of the effective friction angle ϕ' equal to 38.6° and standard deviation $\sigma_{\phi'}$ = 2.63°, whilst the lower portion, typically having a higher fine content, is characterized by ϕ' = 35.6°±1.8°. Both estimates have been obtained from CPTU tests located on the alignment *A-A'*, by applying the Kulhawy and Mayne (1990) correlation, which has proven to be an excellent predictor of the drained strength of clean to slightly dirty sands of quartz, feldspar or other mineralogy. Profiles of the predicted relative density D_r have been found typically to decrease from approximately 75% at ground level to 40% at 5 m in depth, with a mean value $D_{r,avg}$ of the order of 50%. The underlying silty sands are characterized by very low and rather dispersed values of D_r (in the range 20-40%, with $D_{r,avg} \cong 35\%$) although in this case the application of the most common CPTU-based correlations

might be affected by some degree of uncertainty.

As a consequence of their medium-dense to loose state, sands of *Unit A* appears to be rather susceptible to cyclic liquefaction phenomena, as confirmed by the application of the well-known procedure proposed by Idriss and Boulanger (2008) to a number of CPTU tests located along the alignment *A-A'*. Indeed, the liquefaction analysis results have shown that, from 2 m depth to the unit lower boundary, the factor of safety against liquefaction, FoS_{LIQ}, is typically well below unity for an earthquake magnitude M=6.14 and a peak ground acceleration on rock equal to 0.18g, these values being those suggested by the seismic hazard map of the Emilia-Romagna region for a 475-year return period.

As regards *Unit B2*, interpretation of CPTU tests has revealed that such predominantly clayey sediments are typically overconsolidated. As an example, mean values of the oveconsolidated ratio *OCR* calculated on the piezocone tests of section *4-4'* have been found to vary between 2.8 (CPTU 002) and 4.4 (CPTU 505), though without any clear trend in the horizontal direction. Furthermore, a general tendency of *OCR* to decrease with depth has been observed.

As expected for overconsolidated fine-grained sediments, estimates of the undrained shear strength s_u result in values of the ratio s_u/σ'_{v0} significantly higher than those typically observed in *NC* clays (i.e. 0.2-0.3), being on average in the range 0.6-1.0 and having the same trend with depth exhibited by *OCR*. At the same time, the constrained modulus *M*, either determined using the correlation of Kulhawy and Mayne (1990) or the more recent unified method developed by Robertson (2009), is always higher than 10 MPa, at times (as for CPTU 505) close to 20 MPa, thus excluding the risk of excessive settlements due to high soil compressibility. Minor differences have been generally found among the two formulations, although the Robertson's correlation appears to provide slightly higher and significantly more scattered values of *M*.

Finally, the CPTU-based geotechnical characterization of the predominantly silty *Unit B3* must take into account potential partial drainage phenomena during the test (Tonni and Gottardi, 2010; García Martínez et al., 2016). For this reason, the application of correlations

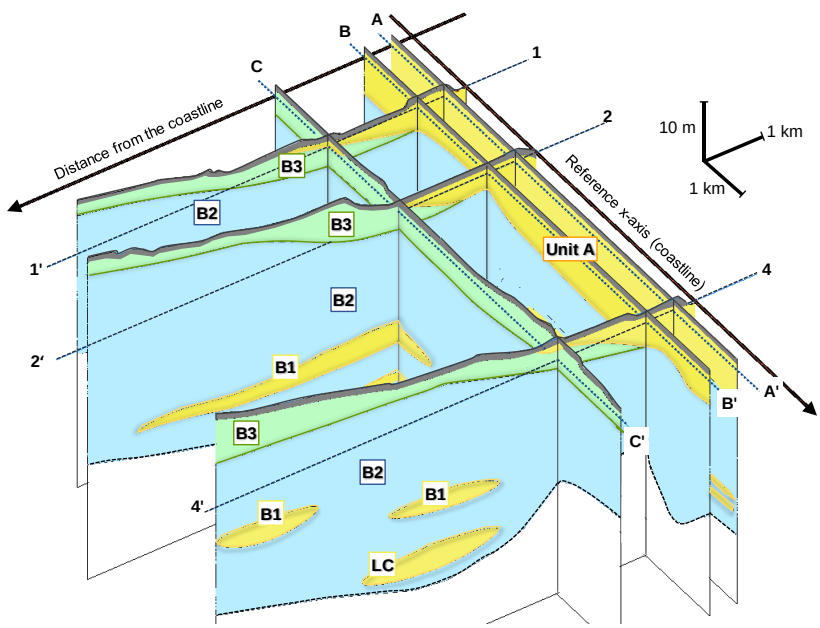

Figure 7. Three-dimensional scheme of the stratigrahic arrangement of the subsoil.

originally developed for clays may result in overestimates of s_u and lead to unsafe design. Hence, the mean values of s_u calculated on the CPTUs located along *4-4'*, though in substantial agreement among them (s_u = 106-115 kPa), must be treated with a certain degree of uncertainty. Similar uncertainties also affect the modulus *M*, whose estimates provided by the correlation for silts of Senneset et al. (1988) appear to be very low (3-4 MPa), about ⅓ of those predicted by the Kulhawy and Mayne (1990) method.

5 CONCLUSIONS

The paper has described the development of a large-scale geotechnical model, concerning the south-eastern coastal plain of the Emilia-Romagna Region (Italy). By performing an accurate geotechnical characterization of the soil units, the study aims at providing some insight into the most appropriate procedures for intepretation of CPTU tests, issues in intermediate soils as well as potential geotechnical problems affecting this coastal area.

6 REFERENCES

Amorosi, A., Cibin, U., Severi, P., Stefani, M., Gabbianelli, G., Simeoni, U., Vincenzi, S. 2004. Late Quaternary evolution of the Po plain from surface and subsurface data: a traverse from the Apennines to the Adriatic Sea. *Proceedings, 32nd Int. Geological Congress*, Vol. 2, B24.

Delgado, J., Alfaro, P., Andreu, J.M., Cuenca, A., Doménech, C., Estévez, A., Soria, J.M., Tomás, R., Yébenes, A. 2003. Engineering-geological model of the Segura River flood plain (SE Spain): a case study for engineering planning. *Engineering Geology* **68**, 171-187.

Dipova, N. 2011. Geotechnical characterization and facies change detection of the Bogacay coastal plain (Antalya, Turkey) soils. *Environmental Earth Sciences* **62**(4), 883-896.

Ferrario, M.F., Bonadeo, L., Brunamonte, F., Livio, F., Martinelli, E., Michetti, A.M., Censi Neri, P., Chiessi, V., Comerci, V., Höbig, N. 2015. Late Quaternary environmental evolution of the Como urban area (Northern Italy): A multidisciplinary tool for risk management and urban planning. *Engineering Geology* **193**, 384-401.

Garcia Martinez, M.F., Tonni, L., Gottardi, G., 2016. On the interpretation of piezocone tests in natural silt and sand mixtures. *Proceedings, Int. Workshop on Metrology for Geotechnics, MetroGeotechnics 2016*,63-68.

Idriss, I. M., Boulanger, R.W. 2008. *Soil liquefaction during earthquakes*. Monograph MNO-12, Earthquake Engineering Research Institute, Oakland, (CA).

Kulhawy, F.H., Mayne, P.H. 1990. *Manual on estimating soil properties for foundation design*. Electric Power Research Intistute (EPRI), Palo Alto (CA).

Robertson, P.K., 2009. Interpretation of cone penetration tests - a unified approach. *Can. Geotech. J.* **46**(11), 1337-1355.

Schneider, J.A., Randolph, M.F., Mayne, P.W., Ramsey, N.R. 2008. Analysis of factors influencing soil classification using normalized piezocone tip resistance and pore pressure parameters. *J. Geotech. Geoenviron. Eng.* **134**(11), 1569-1586

Tonni, L., Gottardi, G. 2010. Interpretation of piezocone tests in Venetian silty soils and the issue of partial drainage. *Deep foundations and geotechnical in situ testing, ASCE Geotechnical Special Publication (GSP)* No. 205, 367-374. ASCE, Reston (VA).

Tonni, L., Rocchi, I., Cruciano, N.P., García Martínez, M.F., Martelli, L., Calabrese, L. 2016. A Multidisciplinary Tool for the Development of a Regional-scale Geotechnical Model: A Case Study in the North-Western Adriatic Coastal Area, *Procedia Engineering* **158**, 546-551.

Senneset, K., Sandven, R., Lunne, T., By, T., Amundsen, T. 1988. Piezocone tests in silty soils. *Proceedings, ISOPT-1*, Vol. 2, 955–966. Balkema, the Netherlands.