Applicability of CPTU to characterize diatomaceous fine-grained soils: a case study in Euganean Hills (Italy)

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ABSTRACT

Diatomaceous soils, composed of diatom fossils and clay minerals typically formed in volcanic environments, exhibit characteristics such as low unit weight, high plasticity and liquid limit, significant compressibility, and high friction angles. Despite their presence in various locations globally, knowledge about their geotechnical behavior is limited and primarily based on laboratory tests conducted on artificial samples. This paper presents data obtained from undisturbed samples of natural diatomaceous soils and discusses the interpretation of Cone Penetration Test with Pore Pressure (CPTU) data to classify these complex non-textbook soils and estimate their mechanical properties.

The study area is situated in the Po Plain near the thermal anomaly region of the Euganean Hills in Northeast Italy. Three CPTUs and one borehole with the collection of four Osterberg undisturbed samples were conducted. Laboratory tests on the undisturbed samples provided values for Atterberg Limits, soil unit weight, in-situ void ratio, compressibility, and permeability, which were compared with estimations derived from CPTU data analysis. Moreover, Scanning Electron Microscope images provided insight into the distinctive microstructure of diatom microfossils embedded in a clayey matrix.

Based on these comparisons, CPTU proves to be effective in estimating relevant parameters of diatomaceous soils, particularly the Soil Behavior Type (SBT) and consolidation coefficient from dissipation tests. However, the agreement in estimating the oedometric modulus is less satisfactory. Therefore, for a precise definition of the geotechnical model, it is recommended to conduct additional laboratory tests, particularly those focused on defining compressibility parameters, given the unique behavior of natural diatomaceous soils.

Keywords: CTPU interpretation; diatomaceous soil; organic soil; oedometer test.

1. Introduction

Diatomaceous soils are mixtures of diatom fossils and clay minerals typically formed in aquatic environment of high silica content. Diatoms are unicellular microalgae distinguished by the presence of a silicified external shell (named frustule) of manifold shapes. The size range of the frustule is between 5-500μm (Zhang et al. 2023). This skeleton is a sort of box, characterized by high strength and a multi-level, honeycomb structure composed by main and secondary transversal ribs (Hamm et al. 2003). The surface is covered by thousands of pores.

Diatomaceous soils are used in a number of industrial, agricultural and chemical applications, but the knowledge on their geotechnical behaviour is poor. Previous research is mainly based on laboratory experiments conducted on artificial mixtures of clay or sand and diatom powder in different percentages (Perisic et al. 2019, Hoang et al. 2022) in order to evaluate changes in mixture engineering properties as diatom content increases. Diatomaceous soils exhibit an unusual behaviour, characterized by low unit weight, high plasticity and liquid limit, high compressibility and high friction angles. In artificial mixtures, higher diatom content, higher friction angle, despite an increasing also of w_L. In addition, with the increase in diatom content, the compressibility increases. However, studies on undisturbed samples of natural diatomaceous soils and in-situ tests are scarce in literature (Caicedo et al. 2018, Zhang et al. 2023). In particular, CPTU data are missing. This is one of the most widely used techniques for on-site investigations, due to its wide range of applicability, rapidity, and generally low costs. Unfortunately, the empirical correlations usually applied for data interpretation have been mostly defined on datasets related to textbook soils. This raises questions about their reliability for diatomaceous soils.

This paper discusses the results of oedometric tests and CPTUs in a natural diatomaceous deposit in the Euganean geothermal area in Northern Italy. The estimations in terms of soil classification and mechanical properties obtained by applying some of the CPTUs most used correlations are tested and compared with the lab test results.

2. Description of the case study

The study case is located on the Po plain in the Northeast of Italy, within a small alluvial valley in the vicinity of the Euganean Hills. Here, an agricultural building (40x13m) recently constructed in a small plain, approximately 80m away from the base of the hill, is experiencing relevant settlements. Three CPTUs and a borehole with Osterberg undisturbed sampling were performed in order to sketch the stratigraphic profile by classifying the formations and to estimate relevant mechanical properties. The soil profile is composed by an almost 30m sequence of Quaternary alluvial deposits down to the bedrock, that is cracked and permeated by pressurized hot water, with several layers of fine sediments mainly defined by the CPTUs as from clayey silts to silty clays, and from silty clays to clays according to Robertson's soil behavior index I_c.

2.1. The Euganean Geothermal field area

The Euganean Hills are an articulated group of more than a hundred hills of volcanic origin (max 600m altitude) in less than 100km^2, consisting of a variety of igneous rocks of Paleogene age and marly limestones (Calderoni et al 1996). In general, these hills have steep slopes that form sharp angles with small alluvial fans formed by streams that drain the hilly area. Due to the presence of alluvial aggradation formed by sandy and silty deposits by the Brenta and Adige rivers in the outer eastern portion of the area, in the lowest part of the depressions surrounding the hills, lacustrine environments with ponds likely developed during the Quaternary period. Consequently, at the base of the hills the deposits primarily consist of fine-grained soils with high organic contents and substantial peaty layers.

The geothermal system is still active and corresponds to the geothermal anomaly called the Euganean Geothermal Field, home to renowned thermal locales. These centers receive over 3,500,000 annual visitors seeking health and beauty treatments involving thermal water and solid mud. More than 142 active wells in the region are fed by meteoric waters originating from the mountainous structures of the pre-Alpine arc. During their descent, reaching depths of up to 3,000m, these waters become enriched in mineral salts, heat up, and ascend to the surface at nearly 100°C, facilitated by the primary regional fault system (Calderan et al 2020). The most exploited aquifer lies between 300 and 500m depth, but many wells reach 800–1000m (Pola et al 2015).

2.2. On site geotechnical investigations

At the vertex of the recently constructed building, three CPTUs down to 20m have been carried out, including also No.5 excess pore pressure dissipation tests, respectively at the depths of 3.08 and 6.07m (in CPTU1), 3.79m (in CPTU2) and 3.44 and 6.46m (in CPTU3). In the last vertex one borehole has been performed down to 20m, also collecting 4 Osterberg undisturbed samples at the depth of 3.2-3.80, 6.20-6.80, 9.20-9.80 and 10.70-11.30m.

The data acquired from CPTUs have been elaborated to evaluate the Robertson's soil behaviour index I_c (Robertson 1990). In Fig.1 the cone tip resistance (q_c), the sleeve friction (f_s) and penetration porewater pressure (u) obtained at 1cm-depth intervals in the three CPTUs are reported, together with the Robertson's soil behaviour index I_c. The stratigraphy, averaged across the four investigation points, comprises an initial anthropic layer of approximately 2m, succeeded by the first organic, highly layered, clayey diatomaceous layer between 2 and 4m. The second, more homogeneous diatomaceous deposit lies between 4.0 and 7.3m, followed by a thin sandy silt layer (7.3-7.7m). Below, a deposit of light-grey clayey layer extends from 7.7 to 17m, interspersed with another thin silty sand layer of about 0.5m thickness (13.4-13.9m). Finally, an organic silty clay layer lies between 17 and 18m, followed by peat up to 20m.

2.3. Laboratory geotechnical characterization

From the extracted core around 20 disturbed samples have been collected with a spacing of 1m, to determine Atterberg Limits and organic content. During the retrieval operations, the disturbed samples were promptly sealed in plastic bags to assess the natural water content w_n, although with a certain degree of uncertainty. In Fig.1 the blue rectangles indicate the depths corresponding to the Osterberg undisturbed samples (named A, B, C, D at increasing depth).

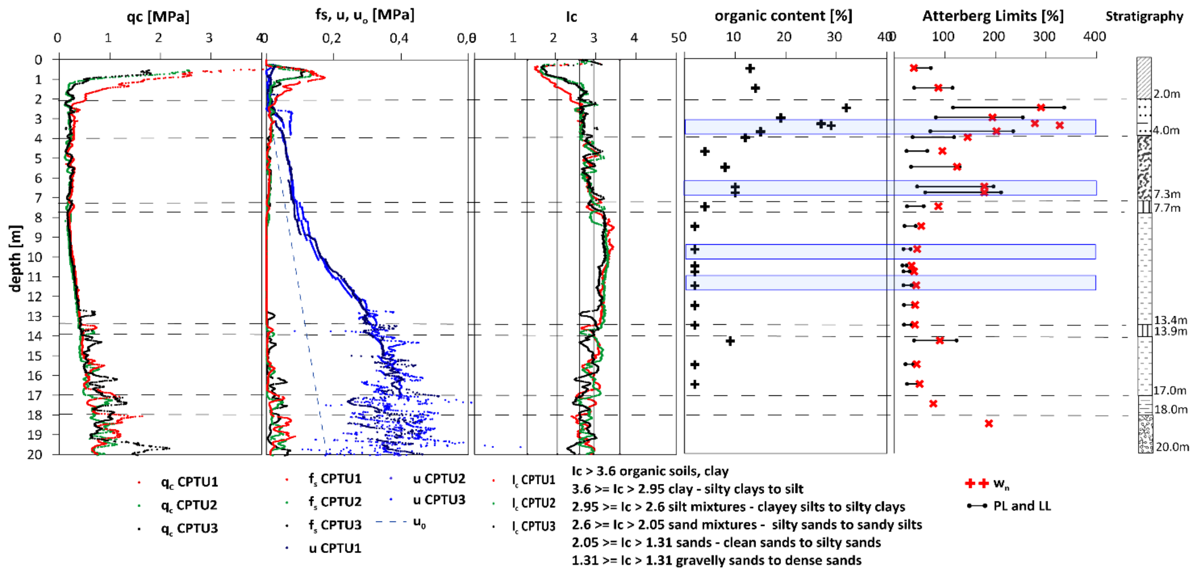

Figure 1. Vertical profile of fs, qc, u acquired from CPTUs, and the evaluated Ic vertical profiles. On the right, vertical profiles of Organic Content and Atterberg Limits; finally, the stratigraphic sequence. The blue rectangles indicate the undisturbed samples.

From the undisturbed samples, natural (γ) and saturated (γ_{sat}) volume unit weights have been determined together with the specific gravity (G_s). Four specimens have been extracted and tested in the oedometric cell to obtain the compression curves (e-$\log\sigma'$ relationship).

Liquid Limits (w_L) and Plasticity Indexes (PI) are consistently high throughout the entire profile, particularly between depths of 2 and 4m (w_L=336, 254, 235; PI=220, 172, 164, respectively); among 6 and 7m (w_L=196, 211; PI=151, 150) and at 18.5m (w_L=249; PI=128). The high liquid limit of diatomaceous soils can be explained by the large intraparticle pores of the frustules, in which a large amount of water is stored. In many cases, the water content exceeds the liquid limit. Furthermore, the organic content remains elevated throughout the vertical profile, reaching maximum values of 32% and 29% at depths of 2.5m and 3.4m, respectively.

Fig.2 shows the location of the samples on the Casagrande Plasticity Chart. All the points are slightly above the *Line A*, indicating clays of high plasticity (*CH*).

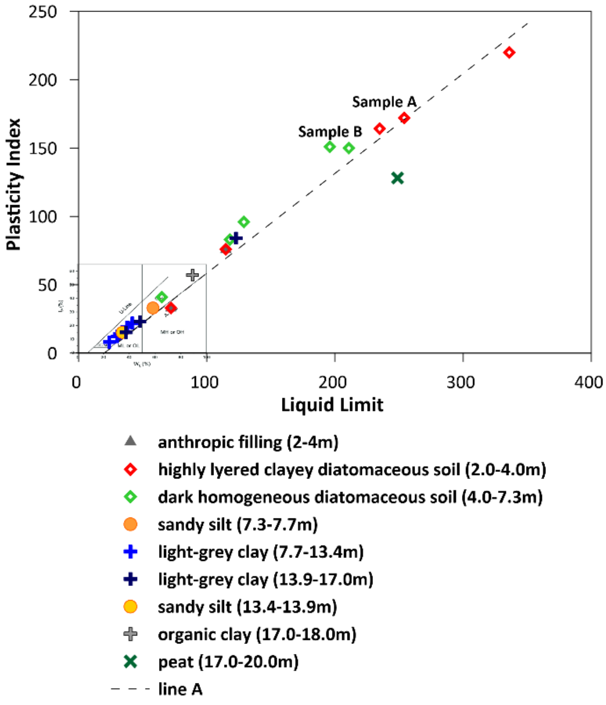

Figure 2. The acquired Atterberg Limits values inserted in the Casagrande Plasticity Chart.

The pictures of the undisturbed samples of diatomaceous soil, A and B, are shown in Fig.3. Both of them appear very light, spongy, highly porous, and elastic. Sample A is heavily layered, with darker and almost white centimetric layers, thus highlighting a succession of periods of different deposition environments, while sample B is very homogeneous and darker. Both have very low values of G_s and volume unit weights, as reported in Table 1.

Figure 3. Laboratory pictures of the undisturbed samples A (a) and B (b).

Table 1. Undisturbed samples Gs and volume unit weights.

Undisturbed sample	G_s	γ **[kN/m^3]**	γ_{sat} **[kN/m^3]**
A: 3.20-3.80	2.356	11.81	12.06
B: 6.20-6.80	2.438	11.33	12.21
C: 9.20-9.80	2.729	16.85	17.17
D: 10.70-11.30	2.728	17.32	17.70

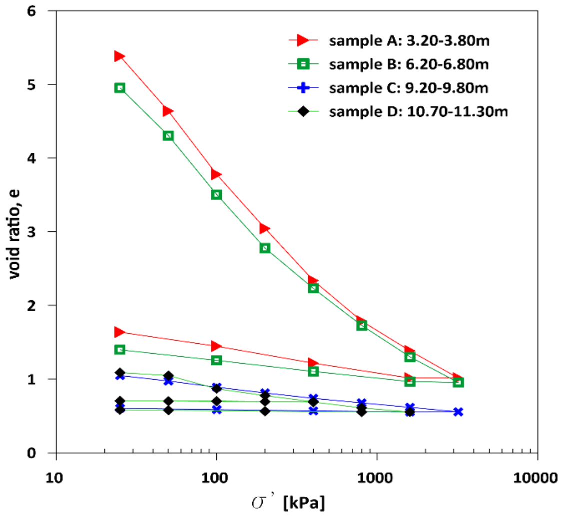

Figure 4. Vertical profile of f_s, q_c and U acquired in CPTU1, and I_c vertical.

The oedometric tests reveal consistently high initial void ratios e_0 for the two shallower samples equal to 4.84 and 5.38, respectively for A and B, and equal to 1.29 and 1.135 for the samples C and D. Fig.4 compares the obtained compression curves; while samples C and D display a behavior typical of soft clays, the samples of diatomaceous soils (A and B) show a very high e_0 and surprisingly high values of Compression and Recompression Indexes C_C and C_R, as reported in Table2. From the consolidation curves, also the value of secondary compression coefficient $C_{\alpha\varepsilon}$ has been evaluated for each loading step, as reported and discussed in Par. 3.3.

Table 2. Acquired compressibility parameters

Undisturbed sample	C_c	C_R	C_c/C_R
A: 3.20-3.80	2.1 (1.28–2.66)	0.31 (0.22-0.36)	6.79
B: 6.20-6.80	1.94 (1.54–2.54)	0.22 (0.17-0.24)	8.96
C: 9.20-9.80	0.528 (0.20–0.27)	0.033 (0.015-0.03)	16
D: 10.70-11.30	0.596 (1.05-0.87)	0.016 (0.55-0.58)	37.3

2.4. Diatomaceous soils

The material of samples A and B was explored using a Scanning Electron Microscope (SEM). The images reveal the high content of diatom microfossils of biological origin. As shown in Fig.5, several typologies of diatoms can be recognized, in particular note the different shapes and dimension of circular *Cocconeis* and elongated *Naviculae*, both typical of the Euganean muds used for therapy issues (Tolomio et al. 2001).

Depending on the frustule shape, two groups can be identified: rounded frustule, with radially symmetric circular shape and pore distribution, and pennate diatom with bilaterally elongated shape (Perisic et al. 2019). Diatoms communities are common in areas characterized by volcanic activities with presence of waters with high silica contents. Therefore, diatomaceous soils form from the deposition of silica skeletons of diatoms together with mineral sediments on lacustrine bottoms or lakebeds.

The wide void volume within the frustules and the presence of thousands of pores results in low unit weight γ, extremely high in situ void ratio e_o, enormous water holding capacity and, therefore, high Atterberg limits and high water contents. These features classify these soils as very soft soil and inorganic clays, as indicated by the Casagrande Plasticity Chart. Nevertheless, they express a resistance to cone penetration higher than that expected, as already observed.

Laboratory analysis of undisturbed samples of natural diatomaceous soils are scarce in literature as well as discussions of on-site geotechnical investigation outputs. Previous research is mainly conducted on artificial mixtures of clay, sand, and diatom powder in different percentages, in order to evaluate changes in engineering properties as diatom content increases. They highlighted that the presence of diatom microfossils in a soil substantially alters its index properties as well as the engineering behaviour (Shiwakoti et al. 2002; Perisic et al. 2019, Zhang et al. 2023). With the increase in diatom content, the compressibility increases. The very high compressibility associated with scarce swelling capacity is attributed to the crushing of diatom microfossils under loading, that is irreversible (Perisic et al. 2019, Zhang et al. 2023). On the other end, higher diatom content, higher friction angle, reaching values around 35-45° despite an increasing also of w_L. The strength increasing is interpreted as a result of particle interlocking and high frictional component due to diatoms surface roughness, different shapes and hard siliceous material (Shiwakoti et al. 2002, Wiemer and Kopf 2017, Perisic et al. 2019).

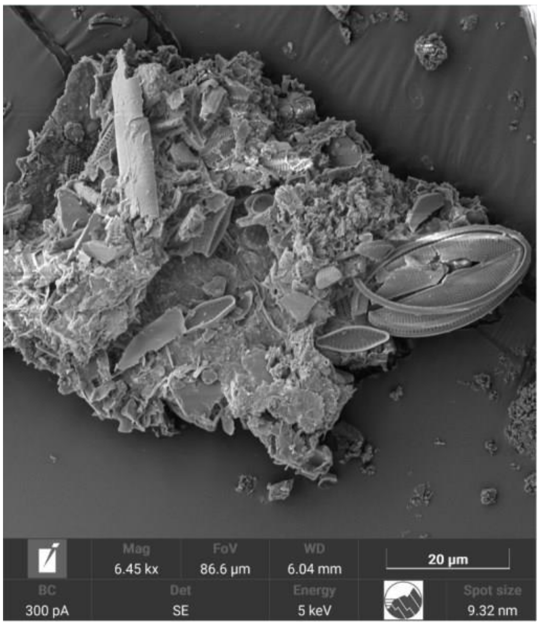

Figure 5. SEM image of Sample A (picture from Prof. Lara Maritan).

3. Discussion of CPTU data interpretation

In the subsequent analysis, the data obtained from the two undisturbed samples of natural diatomaceous soils (samples A and B) are compared with the estimates derived from Cone Penetration Test (CPTU) results. Different relationships commonly employed in CPTU data analysis are applied to discuss their applicability in diatomaceous soils, with particular attention to soil classification, compressibility and permeability parameters evaluations.

3.1. Soil classification and determination of soil behaviour index

In Fig.6, the measured points are superimposed on the CPT-based SBTn classification charts, based on the friction ratio F_r, that is the ratio, expressed as a percentage, of the sleeve friction (f_s), to the cone resistance, q_t, both measured at the same depth; the normalized cone penetration resistance Q_{tn} (dimensionless); and the pore pressure ratio, B_q, that is the net pore pressure normalized with respect to the net cone resistance, defined as follows:

$$F_r = \frac{\mathrm{f}_s}{q_t} \cdot 100\% \tag{1}$$

$$B_q = \frac{\Delta \mathrm{u}}{q_n} \tag{2}$$

$$Q_{tn} = \frac{(q_t - \sigma_{v0})}{\sigma'_{v0}} \tag{3}$$

The two soil layers rich in diatoms are classified here as clays to silty clay (both are located in zone 3 of the soil behavior types charts). Despite the OC around 30%, they do not lay in the organic soils-peat zone (zone 2). This classification in zone 3 is consistent with the soil type.

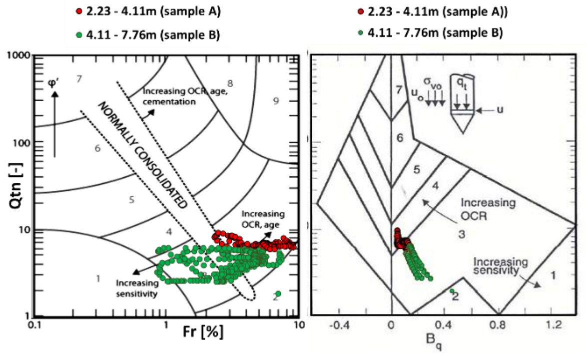

Figure 6. a) Measured points in the CPT-based SBTn charts proposed by Robertson (1990) (charts modified by Robertson 1990) (1=sensitive fine-grained, 2=clay and organic soil, 3=clays, 4=silt-clay mixtures, 5=sand-silt mixtures, 6=sands, 7=dense sand, 8=stiff sand to clayey sand, 9=stiff fine-grained).

3.2. Estimation of soil unit weight

In Fig.7 the soil unit weight provided by lab analysis is compared to the dataset utilized by Mayne (2014) to propose its relationship based on sleeve friction f_s, here reported:

$$\gamma_t = 26 - \frac{14}{1+[0.5\cdot\log(f_s+1)]^2} \tag{4}$$

The points are set in the lower part of the graph, slightly outside the data cluster, in the same area where diatomaceous mudstone and organic peat are positioned.

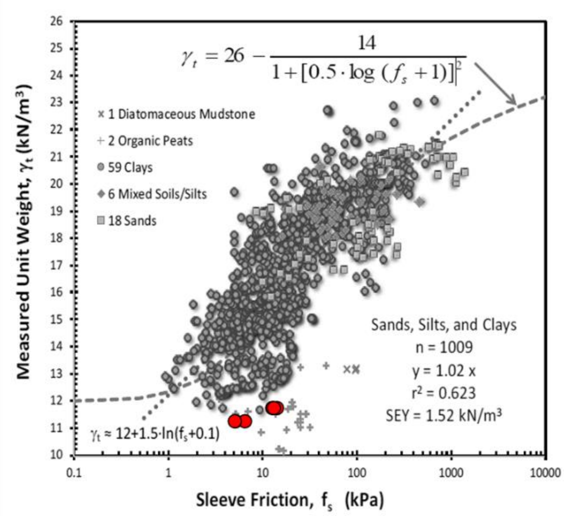

Figure 7. Measured data of unit weight (red points) compared with Mayne's relationship (modified by Mayne 2014).

For each investigation point, the graph in Fig.8 compares the I_c vertical profiles obtained by evaluating the vertical stress using the unit weight calculated by the relationship of Mayne (2014) and the one obtained by applying the correct unit weight provided by the laboratory analysis on the different layers (represented in black). The comparison highlights how the unusually low value of volume unit weight of diatomaceous soils affects the soil layers characterization. Given the limited depth and thickness of the diatomaceous deposit, the I_c is only slightly affected at shallower layers, becoming more significant at increasing depths where the SBT shifts form clays to silty clays.

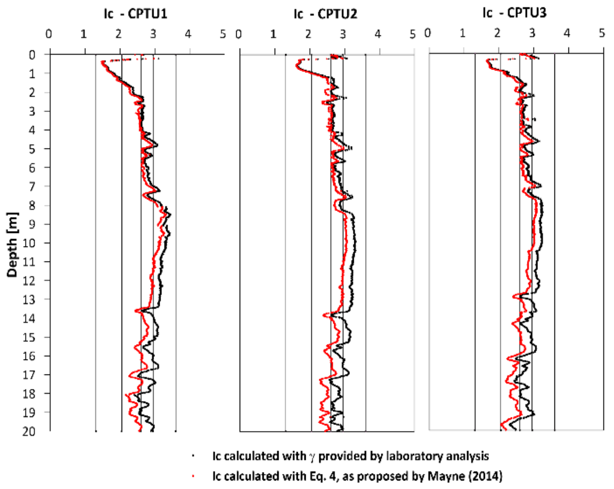

Figure 8. Comparison of the Ic vertical profile in CPTU1, CPTU2 and CPTU3 by applying the value of unit weight calculated with Eq.4 and the one provided by lab analysis.

3.3. Estimation of compressibility parameters

As for the compressibility parameters, the oedometric tests conducted on samples A and B have been elaborated to obtain the oedometric modulus *M* and the Secondary Compression parameter $C_{\alpha\varepsilon}$.

In Fig.9 the values of $C_{\alpha\varepsilon}$ are compared to the dataset used by Tonni and Simonini (2013) to elaborate the relationship between the in situ $C_{\alpha\varepsilon}$ and the related normalized cone resistance Q_{tn} (Eq.3) in similar soils with low organic fraction. They lie slightly above the line defined by the following Eq.5, suggesting that the presence of high organic fraction probably effects an increase of secondary compression of these soils.

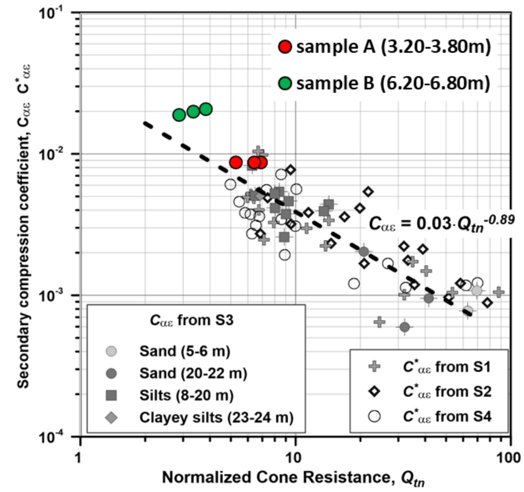

Figure 9. Comparison among the $C_{\alpha\varepsilon}$ obtained by oedometric tests (in red and green for samples A and B) and the relation proposed by Tonni and Simonini expressing the in situ $C_{\alpha\varepsilon}$ as a function of the normalized cone resistance Q_{tn}.(modified from Tonni and Simonini, 2013).

Table 3 directly compares the value of $C_{\alpha\varepsilon}$ to the values obtained from two equations proposed by Tonni and Simonini (2013):

$$C_{\alpha\epsilon} = 0.03\cdot(Q_{tn})^{-0.89} \tag{5}$$

$$C_{\alpha\epsilon} = 0.035\cdot(Q_{tn})^{-0.87}\cdot\left(1+\frac{\Delta u}{\sigma'_{vo}}\right)^{-0.55} \tag{6}$$

Moreover, Table 3 compares the values of the oedometric modulus M with the ones estimated from the cone resistance as proposed by Robertson (2012):

$$M = \alpha_M (q_t - \sigma_{v0}) \tag{7}$$

Where $\alpha_M = Q_{tn}$ when $I_c > 2.2$ and $Q_{tn} < 14$, as in our case. For sample A, the oedometric moduls is underestimated, while a relatively good agreement is found for sample B.

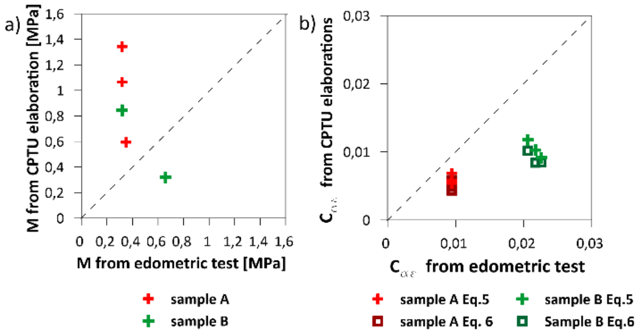

Figure 10. Comparison among M (a) and $C_{\alpha\varepsilon}$ (b) from oedometric tests and CPTU elaborations.

In addition to the estimations based on the CPTU outputs, for the compressibility parameters some simple relationships based on state parameters acquired from laboratory tests have been tested (Azzouz et al. 1976). Among others, we get the estimation based on e_o proposed by Nishida 1956 for all clays:

$$C_c = 1.15 \cdot (e_0 - 0.35) \tag{8}$$

and the following relation, based on w_n (natural water content) proposed by Moran et al. (1958) for organic silts and clays:

$$C_c = 1.15 \cdot 10^{-2} \cdot w_n \tag{9}$$

And, finally we tested also the relationship among C_c and w_L proposed by Terzaghi & Peck (1948):

$$C_c = 0.009 \cdot (w_L - 10) \tag{10}$$

For sample A, the results yield C_c values equal to 5.37, 3.09 and 2.0, respectively, while for sample B, the same equations yield C_c values of 5.78, 2.04 and 1.75. Thus, the estimations based on water content or liquid limit appear more appropriate, as the estimated values are in good agreement with those obtained from laboratory tests, whereas the ones based on the on-site void ratio tend to overestimate the results. This can be related to the fact that in diatomaceous soils the void ratio is composed by four different kinds of voids identified as intra-skeletal pores (the ones within the single diatom microfossil, that are the largest but exist only in case of intact microfossil and depend on the shape), the inter and intra-aggregate pores and the skeletal pores (that are the smallest but highly abundant) (Zhang et al. 2023). The different kinds of voids can be identified also in the SEM image reported in Fig.5.

3.4. Estimation of the permeability and consolidation coefficient

A rough estimation of the permeability k can be derived from the CPTU data, by applying the following relation, valid in case of $1.0 < I_c \leq 3.27$ as in our case (Robertson 2010):

$$k = 10^{(0.952 - 3.04 I_c)} \tag{11}$$

The values are compared with the ones acquired from the variable-head permeameter in oedometric cell for load step of 100kPa, as reported in Table 3 and compared in Fig.11. For sample A, the permeability is significantly overestimated by 2 orders of magnitude, while a better agreement is found for sample B.

The horizontal consolidation coefficient is evaluated from the dissipation tests after having determined t_{50}, i.e. the time corresponding to 50% of excess pore pressure dissipation, with the equation:

$$c_h = \frac{0.245 r^2 \sqrt{I_r}}{t_{50}} \tag{12}$$

Where r is the radius of the cone and the rigidity index I_r is assumed equal to 150.

Considering that the horizontal consolidation coefficient is typically higher than the vertical one measured during oedometric test, it can be concluded that there is a good agreement between the two estimations.

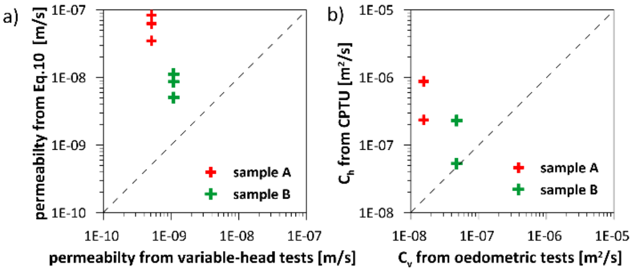

Figure 11. Comparison among (a) consolidation coefficient and (b) permeability parameters.

Table 3. Comparison among the compressibility and permeability parameters.

Undisturbed sample	***M*** *from CPTU* [MPa]	***M*** *from oedom.* [MPa]	$C_{\alpha\varepsilon}$ *from Eq.5*	$C_{\alpha\varepsilon}$ *from Eq.6*	$C_{\alpha\varepsilon}$ *from oedom.*	c_h *from CPTU* [m²/s]	c_v *from oedom.* [m²/s]	***k*** *from CPTU [m/s]*	***k*** *from lab tests [m/s]*
A:3.20-3.80	1.342	0.320	0.005	0.005	0.009	8.93E-07	1.54E-08	8.44E-08	5.13E-10
	1.066		0.006	0.004	0.009	8.63E-07		6.26E-08	
	0.844		0.007	0.006	0.009	2.36 E-07		3.50E-08	
B B:6.20-6.80	0.595	0.350	0.009	0.008	0.023	2.30E-07	4.71E-08	8.64E-09	1.09E-09
	0.376		0.010	0.008	0.022	5.3E-08		1.12E-08	
	0.320		0.012	0.010	0.021			5.07E-09	

4. Conclusions

This paper compares the results of CPTU and laboratory analysis on diatomaceous soil of the Euganean geothermal field in Italy. The laboratory analysis performed on the undisturbed samples highlight that these materials present light unit weight, extremely high liquid limit, in situ void ratio and compressibility.

CPTU classification in terms of SBT is applicable, given that the correct soil unit weight is used. Indeed, the relationship by Mayne (2014) to determine γ overestimates significantly the parameter. The Robertson's classification methods define the tested natural diatomaceous soil as silt mixtures, from clayey silts to silty clays, despite the very high Atterberg Limits, organic content and natural water content.

The coefficient of secondary compression estimated from CPTU with the equation by Tonni and Simonini (2013) is slightly underestimated compared to laboratory values. With respect to oedometric modulus and permeability, the agreement is almost satisfactory for sample B, but poor for sample A, probably the one with higher diatoms content. This is not surprising considering that CPT is known to be not very reliable to estimate these parameters.

Very good agreement is found for the consolidation coefficient from dissipation tests and oedometric test.

In conclusion, in this case, CPTU appears to be applicable to estimate some relevant parameters of diatomaceous soils. Nevertheless, for the definition of the geotechnical model it is recommended to acquire the results of additional laboratory tests, in particular aimed at defining the compressibility parameters, given the uncommon behaviour of this kind of natural soils.

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References

Azzouz, A. S., Krizek, R. J., Corotis, R. B. "Regression analysis of soil compressibility". Soil Found, 16(2), pp.19-29, 1976.

Caicedo, B., Mendoza, C., López, F., Lizcano, A. "Behavior of diatomaceous soil in lacustrine deposits of Bogotá, Colombia", J Rock Mech Geotech Eng, 10(2), PP. 367-379, 2018. https://doi.org/10.1016/j.jrmge.2017.10.005

Calderan A., Carraro A., Honisch C., Lalli A., Ruzza P., Tateo F. "Euganean therapeutic mud (NE Italy): Chlorophyll a variations over two years and relationships with mineralogy and geochemistry", App Clay Sci, 185 (105361), 2020. https://doi.org/10.1016/j.clay.2019.105361

Calderoni, G., Castigliani G.B., Foddai D., Gallio S., Lombardo M., Miola A., Zangheri P. "Paleoenvironmental features of a peri-euganean (Padua, Northern Italy) depression during the late Quaternary: first results", Italian J Quater Sci, 9 (2), pp. 667-670, 1996.

Hamm, C. E., Merkel, R., Springer, O., Jurkojc, P., Maier, C., Prechtel, K., Smetacek, V. "Architecture and material properties of diatom shells provide effective mechanical protection". Nature, 421(6925), pp. 841-843, 2003. https://doi.org/10.1038/nature01416

Hoang, N. Q., Kim, S. Y., Lee, J. S. "Compressibility, stiffness and electrical resistivity characteristics of sand–diatom mixtures". Géotechnique, 72(12), pp. 1068-1081, 2022. https://doi.org/10.1680/jgeot.20.P.136

Mayne, P. W. "Interpretation of geotechnical parameters from seismic piezocone tests", In: Proceedings, 3rd International Symposium on Cone Penetration Testing, Las Vegas, Nevada, USA, 2014, pp.47-73.

Perisic G. A., Ovalle C., Barrios, A. "Compressibility and creep of a diatomaceous soil", Eng Geol, 258, 105145, 2019. https://doi.org/10.1016/j.enggeo.2019.105145

Pola M., Fabbri P., Piccinini L., Zampieri D. "Conceptual and numerical models of a tectonically-controlled geothermal system: a case study of the Euganean Geothermal System, Northern Italy", Cent Eur Geol, 58, pp. 129-151, 2015. https://doi.org/10.1556/24.58.2015.1-2.9

Robertson, P. K. "Estimating in-situ state parameter and friction angle in sandy soils from the CPT". In: Proceedings, 2nd International Symposium on Cone Penetration Testing, CPT'10, Huntington Beach, CA, USA, 2010.

Robertson, P. K. "Interpretation of in-situ tests–some insights". Mitchell Lecture-ISC, 4, 1-22, 2012.

Robertson, P. K. "Soil classification using the cone penetration test", Can Geotech J, 27(1), pp.151-158, 1990.

Shiwakoti, D. R., Tanaka, H., Tanaka, M., Locat, J. "Influences of diatom microfossils on engineering properties of soils". Soils Found, 42(3), 1-17, 2002. https://doi.org/10.3208/sandf.42.3_1

Terzaghi, K., Peck, R. B., Mesri, G. "Soil mechanics in engineering practice", John Wiley & Sons, New York (USA), 1996.

Tolomio, C., Moschin, E., Ceschi Berrini, C., Moro, I., De Apollonia, F "Guida alla conoscenza dei micro-organismi vegetali nelle Terme Euganee", Università di Padova – Dip. di Biologia, 2001. (*in italian*)

Tonni, L., Simonini, P. "Evaluation of secondary compression of sands and silts from CPTU". Geomech and Geoeng, 8(3), pp. 141-154, 2013, 154. http://dx.doi.org/10.1080/17486025.2012.726748

Wiemer, G., Kopf, A. "Influence of diatom microfossils on sediment shear strength and slope stability". Geochemistry, Geophysics, Geosystems, 18(1), 333-345, 2017. https://doi.org/10.1002/2016GC006568

Zhang X.., Liu X., Xu Y., Wang G., Ren Y. "Compressibility, permeability and microstructure of fine-grained soils containing diatom microfossils". Géotechnique, 1-15, 2023. https://doi.org/10.1680/jgeot.22.00155