Interpretation of CPTu in “unusual” soils

Diego Lo Presti,* Ilaria Giusti,** Barbara Cosanti,*** Nunziante Squeglia,**** Ermanno Pagani*****

Summary

The paper deals with the interpretation of CPTu in unusual soils, such as shallow clayey layers above the water table and loose, intermediate - permeability soils (loose silt mixtures).

The paper shows an approach that could be used for the first type of soil to infer the effective vertical stress from CPTu measurements and in particular from the Ic index. The approach has been checked on a very limited amount of experimental evidence. Moreover, an empirical correction of the Ic index is provided in order to obtain a more realistic soil profiling of loose silt mixtures. The foundation soils of the Serchio River levee system and some dredged sediments, which had been stored in the Port of Livorno, have been considered for the second type of soil.

1. Introduction

Cone penetration tests (CPTs) are mainly used for an indirect evaluation of soil profiles, as well as for the assessment of mechanical/hydraulic soil parameters with depth, the assessment of liquefaction susceptibility and the direct assessment of the Ultimate Limit State (ULS) and Serviceability Limit State (SLS) of shallow/deep foundations. A cost – effective investigation campaign should consider both CPTs (and/or other in situ tests) and boreholes. For obvious reasons, the reference soil profile should be inferred by means of direct investigation tools (*i.e.* boreholes), while CPTs, after an appropriate calibration, should be used for confirmation purposes, especially for large investigation areas. However, CPT interpretation always requires a preliminary “Soil Behavior Type (SBT)” identification.

Soil profiling using mechanical CPT (CPTm), electrical CPT (CPTe) or piezocone (CPTu) can be performed by means of empirical (or semi – empirical) approaches [Begemann, 1965; Schmertmann, 1978; Searle, 1979; Douglas and Olsen, 1981; Robertson *et al.*, 1986; Robertson, 1990; Jefferies and Davies, 1993; Eslami and Fellenius, 1997]. These approaches refer to different databases and mainly consider “conventional soil” *i.e.* saturated clays/silts/sands or their mixtures. These databases consider “well – educated” soils, but not unusual soils such as: a) soil layers above the water table with relevant suction effects, b) partially saturated soils (partial drainage conditions), c) compacted soils (earthworks), d) very loose silt mixtures with intermediate permeability, d) underconsolidated soils, etc. In any case, the applicability of the currently available empirical approaches in a different context becomes questionable.

In the Authors experience, the available classification systems (CPTu) have not led to a correct SBT identification of the loose silt mixtures that they have encountered in different contexts. More specifically, very loose silt mixtures have been found within the chaotic dredged sediments stored in the artificial basin of the Port of Livorno and in the case of loose silt mixtures of the Serchio River levee – system and its foundation soil [Cosanti *et al.,* 2012]. The poorly compacted silt mixtures of the Serchio River levee - system and the loose silt mixtures of the foundation soil of these levees are often classified as clay or even organic clay. A similar systematic type of miss - classification was also observed in the case of dredged sediments of the Livorno Port artificial basin. The term miss – classification here refers to SBT classes and not to the grain size distribution and Atterberg Limits.

Soil layers above the water table may be partially saturated. In this situation, the cone penetration occurs under a partial drainage condition. While the effect of saturation degree appears quite negligible for sands [Schmertmann, 1976; Bellotti *et al.,* 1988; Jamiolkowski *et al.,* 2001], it may become very relevant for fine – grained soils. Jamiolkowski *et al.* [2001] analyzed CPTu test results in a Calibration Chamber on dry or fully saturated, reconstituted sand samples. They found that the tip resistance of fully saturated samples is slightly lower than that of dry samples (at the same relative density and boundary stresses) for fine to medium sands.

However, even when soil layers are fully saturated by capillarity, the in situ stress state is controlled

---

* D. Lo Presti (Associate professor - University of Pisa, DESTeC)
** I. Giusti (Doctoral student - University of Pisa DESTeC)
*** B. Cosanti (Post - Doc. Researcher - University of Pisa DESTeC)
**** N. Squeglia (Researcher, University of Pisa DESTeC)
***** E. Pagani (Holder Pagani Geotechnical Equipment - PC)

by suction, which is usually not known. The possible effects of suction on soil profiling, in the case of fine-grained soil deposits, can lead to another type of miss – classification, that is, overconsolidated clays (because of suction) are sometimes erroneously identified as sands. This is also a consequence of the fact that, for practical reasons, only the pore pressure behind the tip (U2) is measured.

This paper proposes two different approaches that could be used to overcome some of the above mentioned problems and to obtain a better interpretation for some "unusual" soils. Two different methodologies are here proposed for a more accurate CPT interpretation. The first methodology results in a better estimate of the effective stress state in soil layers above the water table (suction estimate). To this end, the modified Kovacs model (MK) has been used in the first step. Details of the model can be found in the original work by Kovacs [1981] and in the subsequent paper by Aubertin *et al.* [2003]. This method offers the possibility of estimating the soil suction from simple physical soil parameters (*i.e.* from soil classification). In the second step, the I_c index has been used to obtain a more realistic estimate of the in situ effective stresses. Such a methodology has been applied to re - interpret the CPTu carried out in two different sites. The second methodology is purely empirical, and consists of a calibration of the I_c values [Robertson, 1990; Jefferies and Davies, 1993], as inferred from CPTu results, with evidence obtained from direct logging (boreholes) in the case of very loose silt mixtures. This methodology has been applied to the foundation soil of the Serchio River levee system and to some dredged sediments that had previously been stored in the artificial basin of the Livorno Port.

2. Evidence of some profiles of unusual soils

Figure 1a shows the I_c values with depth of three CPTu carried out along the Serchio River Levees. The tests were extended down to about 30 m and included the River embankment, for the first 4 m, and the foundation soils. Two aspects can be observed:

- the I_c values in the upper meters indicate the presence of sand and sand mixtures;
- the I_c values, at depths of 10, 20 and 30 meters, indicate the presence of organic clays;

In both cases, the indications obtained from the CPTu interpretation appear to contrast the borehole evidence. In the first case, the miss – classification may be a consequence of partial saturation and in particular due to the fact that suction was not taken into account. The second type of miss – classification is a consequence of the inability of the currently available approaches to correctly identify very loose silt mixtures.

The I_c values from two CPTus, which were carried out at the same location (Broni) in different periods, are shown in figure 1b [Meisina, 1996]. The deposit is homogeneous and on the basis of laboratory testing on undisturbed samples retrieved from the first three meters was mainly classified as CL to CH. The water table was found at a depth of 3.5 m during the wet season (June 2001) and at a depth of 5 m during the dry season (September 2001). The two CPTus were carried out at the same location (the distance between the two CPTus and boreholes was about 0.5 m) in June and September 2001. Figure 1c (Meisina, 1996) shows the location of the boreholes, CPTus and a number of wells. In spite of the homogeneity of the deposit, it can be observed that the tip resistance (qc) is influenced to a great extent by the water table depth (suction) so that qc increases from 1 – 2 MPa to 3 – 4 MPa in the vadose zone above the water table (Fig. 2). It is worth noticing that such an increase is higher during the dry season. The effect of suction on the I_c values and SBTn classes (Robertson, 1990) is shown in the subsequent figures 10 to 13. As far as the I_c index is concerned, the values decrease from about 3 at the water table depth to about 2.0 at a depth of 50 cm. In terms of SBTn classes, silts and sand mixtures become predominant instead of OC stiff clay (SBTn class 9).

3. The MK model

More information about the model can be found in the works by Kovacs [1981] and Aubertin *et al.* [2003]. The MK model has been used to evaluate the matrix suction (ψ_r) at the residual water content and the equivalent capillary height above the water table (h_{co}) from simple soil parameters [Aubertin *et al.*, 1998; Mbonimpa *et al.*, 2000; 2002]. For granular soils $h_{co,G}$ (the suffix "G" stands for granular soils) can be considered equivalent to the height of the capillary fringe, and can be evaluated using the following expression:

$$h_{co,G}=\frac{b}{eD_{10}} \qquad (1)$$

$$b\,[\mathrm{cm}^2]=\frac{0.75}{1.17\cdot\log(C_U)+1} \qquad (2)$$

where: e = void ratio and $C_U=\frac{D_{60}}{D_{10}}$ is the coefficient of uniformity. Kovacs [1981] defined the following parameter (equivalent particle diameter), embedded in equations (1) and (2), for heterogeneous material:

$$D_H=[1+1.17\cdot\log(C_u)]\cdot D_{10} \qquad (3)$$

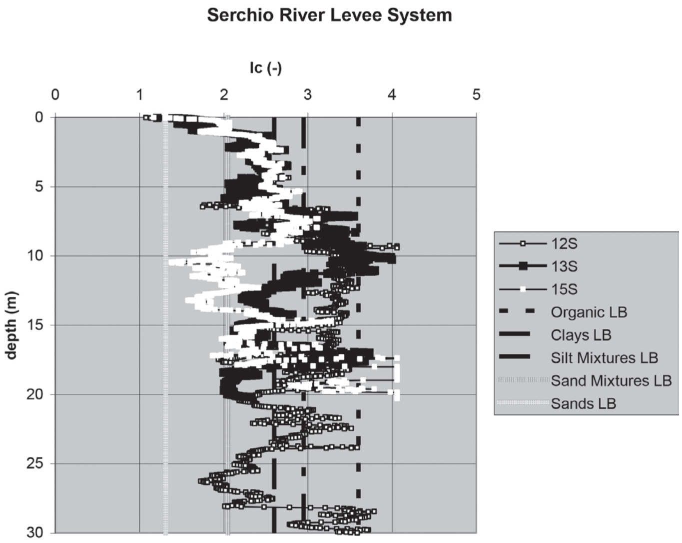

Fig. 1a – CPTu results - the Serchio River embankments and foundation soil (CPTu 12S, 13S, 16S) – LB = Lower Bound.
Fig. 1a – Risultati prove CPTu relative agli argini del fiume Serchio e del terreno di fondazione (CPTu 12S, 13S, 16S) – LB = Limite Inferiore.

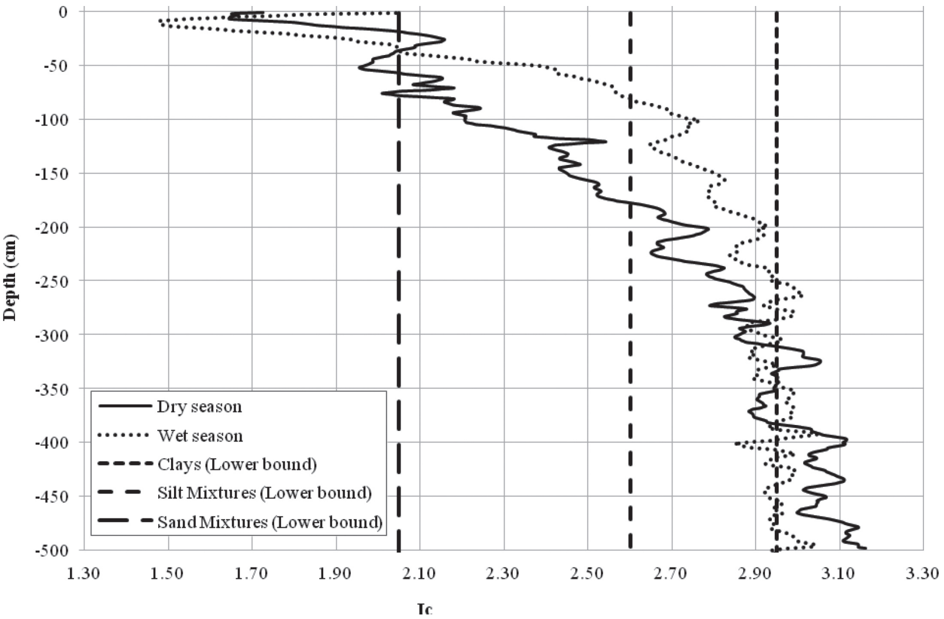

Fig. 1b – CPTu results - Broni (PV – Italy).
Fig. 1b – Risultati prove CPTu - Broni (PV – Italy).

For fine grained (plastic, cohesive) materials (the suffix P stands for plastic soils), the following expression is more appropriate:

$$h_{co,P} = \frac{\xi}{e} w_L^{1.45} \tag{4}$$

where: w_L is the liquid limit and $\xi(\mathrm{cm}) \approx 0.15\rho_s(\mathrm{Kg/m^3})$ (ρ_s = solid density)

The MK model uses h_{co} as a reference value to define the relationship between the degree of saturation and the matric - suction ψ. The suction at residual water content is defined as follows:

$$\psi_r = \frac{0.42}{(eD_H)^{1.26}} \tag{5}$$

For granular materials:

$$\psi_r = 0.86 \cdot h_{co,G}^{1.2} \tag{6}$$

For clayey soils:

$$\psi_r = 0.86 \left(\frac{\xi}{e}\right)^{1.2} w_L^{1.74} \tag{7}$$

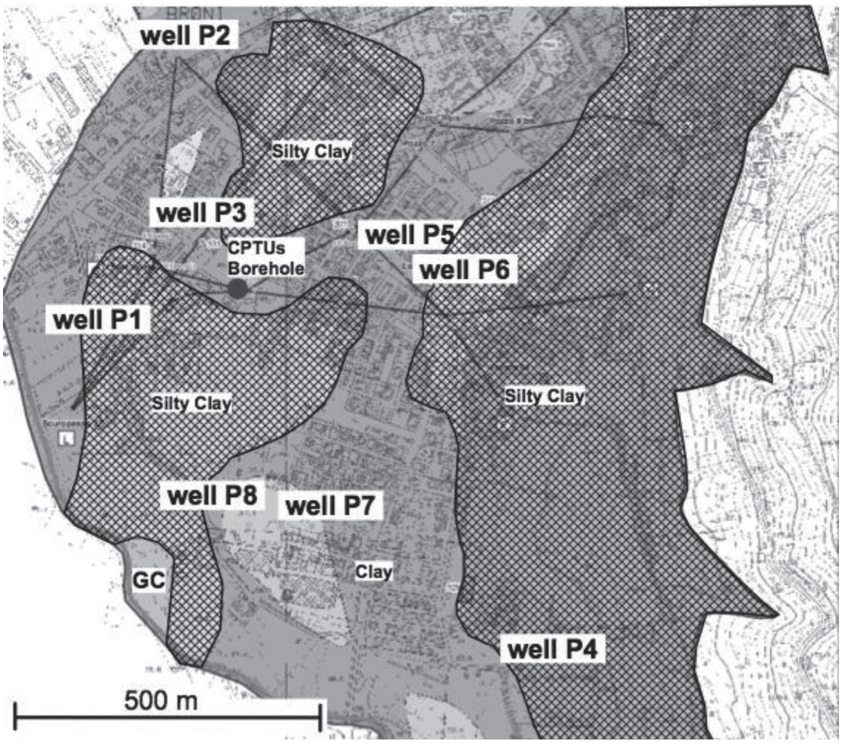

Fig. 1c – Broni area – Geological map, test and well (P1 to P7) locations.
Fig. 1c – Area di Broni – Carta Geologica, ubicazione delle prove e dei pozzi (P1 - P7).

In order to take in to account the influence of suction on the interpretation of the test results, a negative pore water pressure was computed above the water table according to the following equations:

$$u=-\gamma_w h \text{ (for } 0<h<h_{co}) \qquad (8)$$

$$u=-\gamma_w h_{co} \text{ (for } h>h_{co}) \qquad (9)$$

h = height above the water table. The adopted hypotheses obviously represent an oversimplification and may still underestimate the effective stresses.

4. Reinterpretation of CPTu at Broni

Broni is in the North of Italy in the Po River area near Pavia. From a geological point of view, it is characterized by alluvial deposits that have been generated by the Po River and its tributaries. Over the years, geotechnical investigations, including geotechnical soundings and CPTu tests conducted at various depths of between 20m and 30m [Meisina, 1996; Lo Presti *et al.*, 2009], have been carried out by the University of Pavia. Moreover, data from 8 wells are available [Meisina, 1996]. These wells are located in the residential area of Broni, and were used to monitor the water table depth from July 2002 to July 2003 (Tab.I). Well P3 (Fig. 1c) is the closest one to the CPTus and borehole.

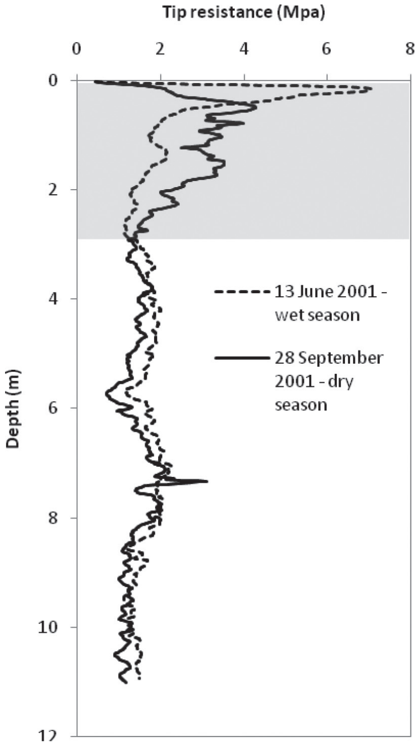

Fig. 2 – CPTu1 and CPTu2 (Broni). The highlighted layer shows the zone of influence of seasonal changes of the water table.
Fig. 2 – Prove CPTu1 and CPTu2 (Broni). Lo strato evidenziato individua la zona interessata dalla variazione stagionale della profondità di falda.

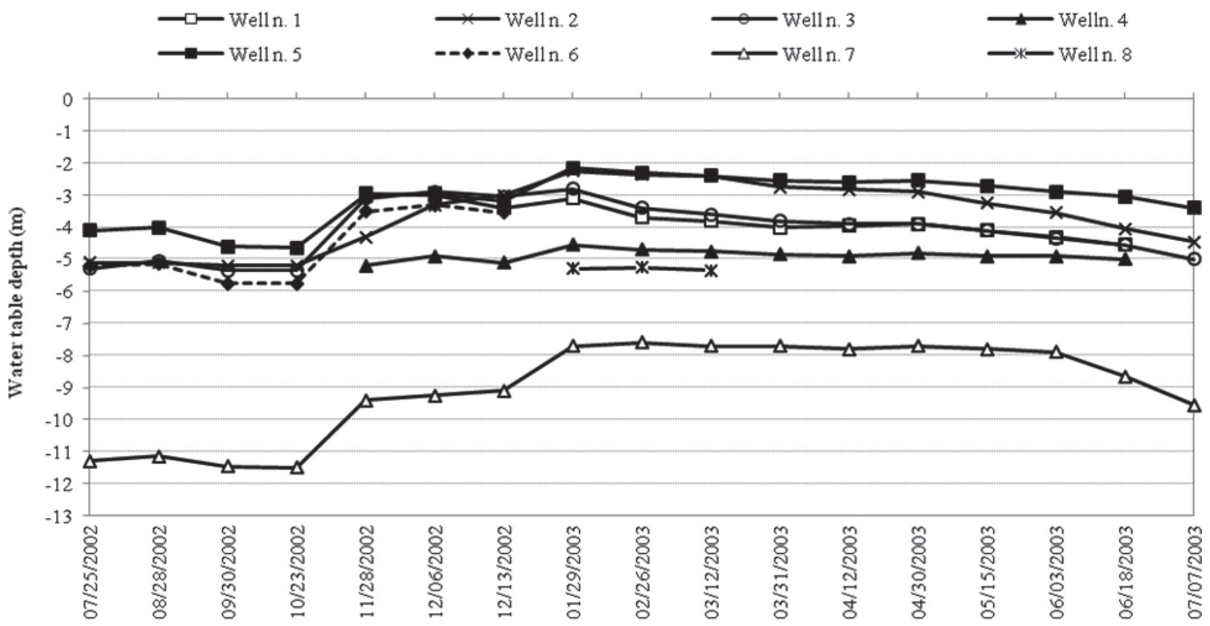

Fig. 3 – Water table depth during the observation period, residential area of Broni [Meisina, 1996].
Fig. 3 – Soggiacenza della falda monitorata nel periodo di osservazione, area residenziale di Broni [Meisina, 1996].

Almost all the wells reach a depth of between 5.4 and 12 meters and their levels are therefore controlled by the superficial aquifer, while well P7, with a depth of 18.5, meters is believed to reach the principal and deeper aquifer

It is possible to observe from figure 3 and figure 4 that the water level follows the pluviometric levels and reaches a maximum in January. The pluviometric range for the superficial aquifer is about 2-2.5 m, while it reaches 3.8 meters for the deeper aquifer. The observed trend of the water table depth with time, over the whole area, confirms the correctness of the measured values that have been considered to interpret CPTu1 and CPTu2.

4.1. Cone Penetration tests

The results of the two CPTu tests (the same as those in figures 1b and 2) are shown in figure 5 and figure 6. The possible effects of suction on the q_c and I_c values have already been mentioned. The layer in which it is possible to observe differences between tip resistances related to a different suction is highlighted in figure 2. It is not possible to ascertain beyond reasonable doubt the reasons for the differences in q_c for the first 0.5 m. However, it is possible to hypothesize local texture heterogeneities (man – made soil).

As far as the pore water pressure measurements are concerned, an almost nil value of U2 can be ob-

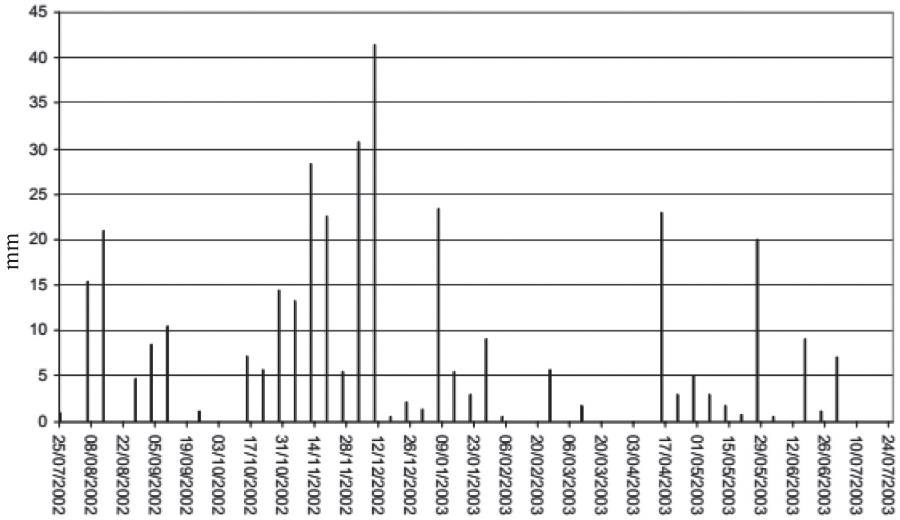

Fig. 4 – Pluviometric levels at Cigognola station (Pavia) – Meisina [1996].
Fig. 4 – Intensità di pioggia rilevata alla stazione di Cigognola (Pavia) – Meisina [1996].

Tab. I – Water Table Depth from July 2002 to July 2003, residential area of Broni. NA = Not Available (i.e. Dry Well).

Tab. I – Soggiacenza della falda dal luglio 2002 al luglio 2003, area residenziale di Broni. NA = Non disponibile (Pozzo asciutti).

Date	Well n. 1	Well n. 2	Well n. 3	Well n. 4	Well n. 5	Well n. 6	Well n. 7	Well n. 8
7/25/2002	NA	-5,1	-5,3	NA	-4,1	-5,2	-11,3	NA
8/28/2002	NA	-5,1	-5,05	NA	-4	-5,15	-11,15	NA
9/30/2002	NA	-5,2	-5,35	NA	-4,6	-5,75	-11,45	NA
10/23/2002	NA	-5,2	-5,35	NA	-4,65	-5,75	-11,5	NA
11/28/2002	-2,95	-4,3	-3,1	-5,2	-3	-3,5	-9,4	NA
12/06/2002	-3	-3,3	-2,9	-4,9	-2,95	-3,3	-9,25	NA
12/13/2002	-3,4	-3	-3,05	-5,1	-3,2	-3,55	-9,1	NA
1/29/2003	-3,1	-2,25	-2,8	-4,55	-2,15	NA	-7,7	-5,3
2/26/2003	-3,7	-2,35	-3,4	-4,7	-2,3	NA	-7,6	-5,25
03/12/2003	-3,8	-2,4	-3,6	-4,75	-2,4	NA	-7,7	-5,34
3/31/2003	-4	-2,75	-3,8	-4,85	-2,55	NA	-7,7	NA
04/12/2003	-3,95	-2,82	-3,9	-4,9	-2,6	NA	-7,8	NA
4/30/2003	-3,9	-2,9	-3,9	-4,8	-2,55	NA	-7,7	NA
5/15/2003	-4,1	-3,25	-4,1	-4,9	-2,7	NA	-7,8	NA
06/03/2003	-4,3	-3,55	-4,35	-4,9	-2,9	NA	-7,9	NA
6/18/2003	-4,55	-4,05	-4,55	-5	-3,05	NA	-8,65	NA
07/07/2003	NA	-4,45	-5	NA	-3,4	NA	-9,55	NA

W_l e W_p = Limite Liquido e Limite Plastico; W = contenuto d'acqua naturale; S = grado di saturazione; e_o = Indice dei vuoti; h_{co} = Altezza di risalita capillare da prove di laboratorio; σ_g = pressione di rigonfiamento da prove di laboratorio.

served until a depth of about 2 m for CPTu1, and the dynamic pore water pressure then increases with depth, until lower values than 25 kPa are reached. These measurements cannot be considered satisfactory because they indicate an initial de-saturation of the filter and subsequent sluggish measurements. On the other hand, the dynamic pore water pressure assumes negative values at depths of between zero and -2.5 meters during the CPTu2 test, after which it increases with depth. The high pore water pressure value observed at -0.5 meters could be explained by considering the extreme stiffness of the shallower

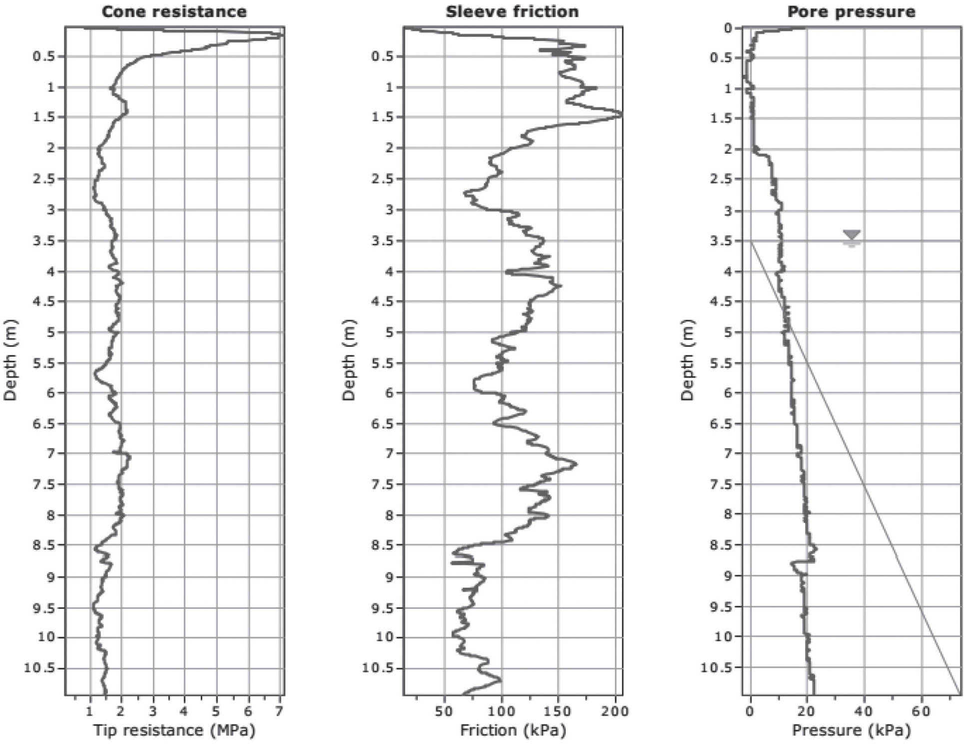

Fig. 5 – CPTu1 conducted during the humid season (Broni).

Fig. 5 – Prova CPTu1 eseguita nel corso della stagione umida (Broni).

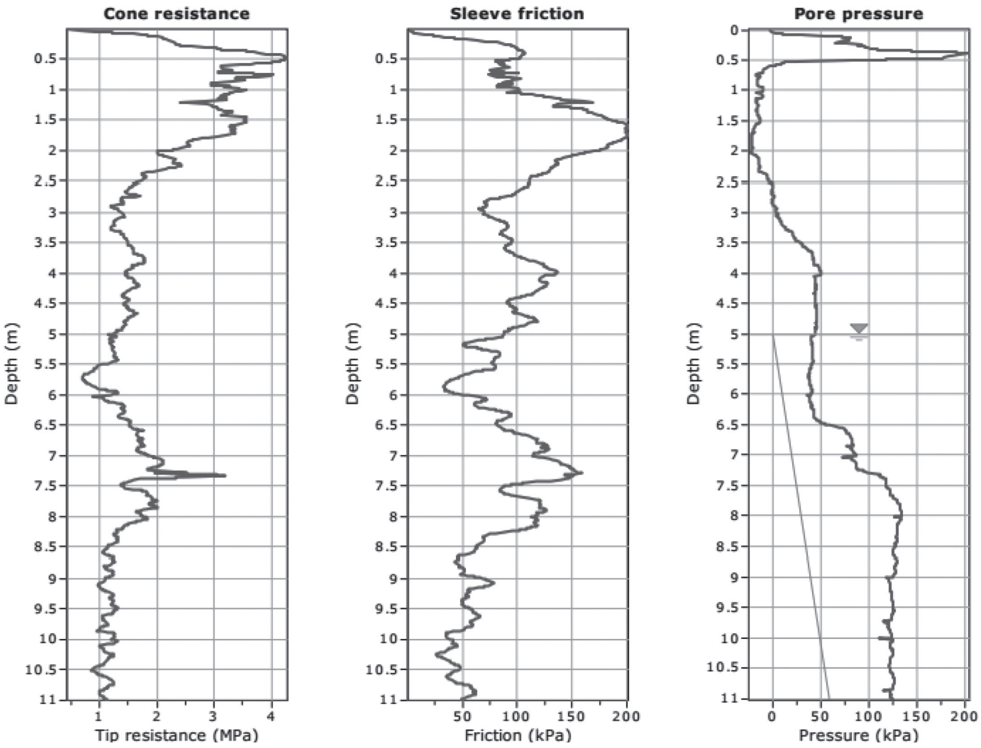

Fig. 6 – CPTu2 conducted during the dry season (Broni).
Fig. 6 – Prova CPTu2 eseguita nel corso della stagione asciutta (Broni).

layer (man – made soil) and the consequent compressibility of the tip (including the filter). In the same way, as for CPTu1, this could be the cause of filter de – saturation.

The unsatisfactory measurement of U2 during the CPTu1 test does not influence the proposed method which pertains to the reinterpretation of the first 3 m using the total tip resistance and friction ratio. In fact the differences between the measured and total tip resistance for CPTu2 are negligible.

The pore water pressure was measured using silicone grease (very fluid, NLGI 00) as the slot filter saturation fluid. The use of grease as a saturation fluid was first proposed by ELMGREN [1995] and LARSSON [1995], and various comparisons have testified its reliability. In addition, a calibration procedure was performed at Pagani Geotechnical Equipment (PC – Italy). Figure 7 shows the piezocone calibration test which was conducted in a specially devised calibration chamber: the upper diagram shows the relationship between the applied loads and readings during loading and unloading, while the lower diagram shows the calculated error, expressed as a percentage of the maximum applied pressure, during both the loading and unload-

Tab. II – Soil classification (Broni – first three meters) [MEISINA 1996].
Tab. II – Classificazione del terreno (Broni – primi tre metri) [MEISINA 1996].

Sample	Depth (cm)	W_l (%)	Wp (%)	W (%)	gd (kN/m^3)	S (%)	e_0	h_{co} (m)	σ_g (kPa)
B1	87	61	26	29.30	14,5	91,00	0,862	2,8	20
B2	130	59	28	27.90	15,1	96,00	0,788	2,7	15
B3	170	51	24	27.90	151	92,00	0,788	3,0	25
B4	200	49	19	27.00	15,4	96,00	0,753	2,6	15
B5	215	51	23	29.80	15,5	93,00	0,742	2,5	23
B6	230	44	25	30.00	14,7	97,00	0,837	2,6	8
B7	250	39	26	28.00	14,7	92,00	0,837	2,3	0
B8	263	41	22	26.00	15,5	95,00	0,741	2,5	13
B9	300	60	24	28.80	15,3	97,00	0,765	2,7	10

W_l and W_p = Liquid and plastic limit respectively; W = natural water content; S = Saturation degree; e_o = Void ratio; h_{co} = Capillary rise from lab tests; σ_g = Swelling pressure from lab tests.

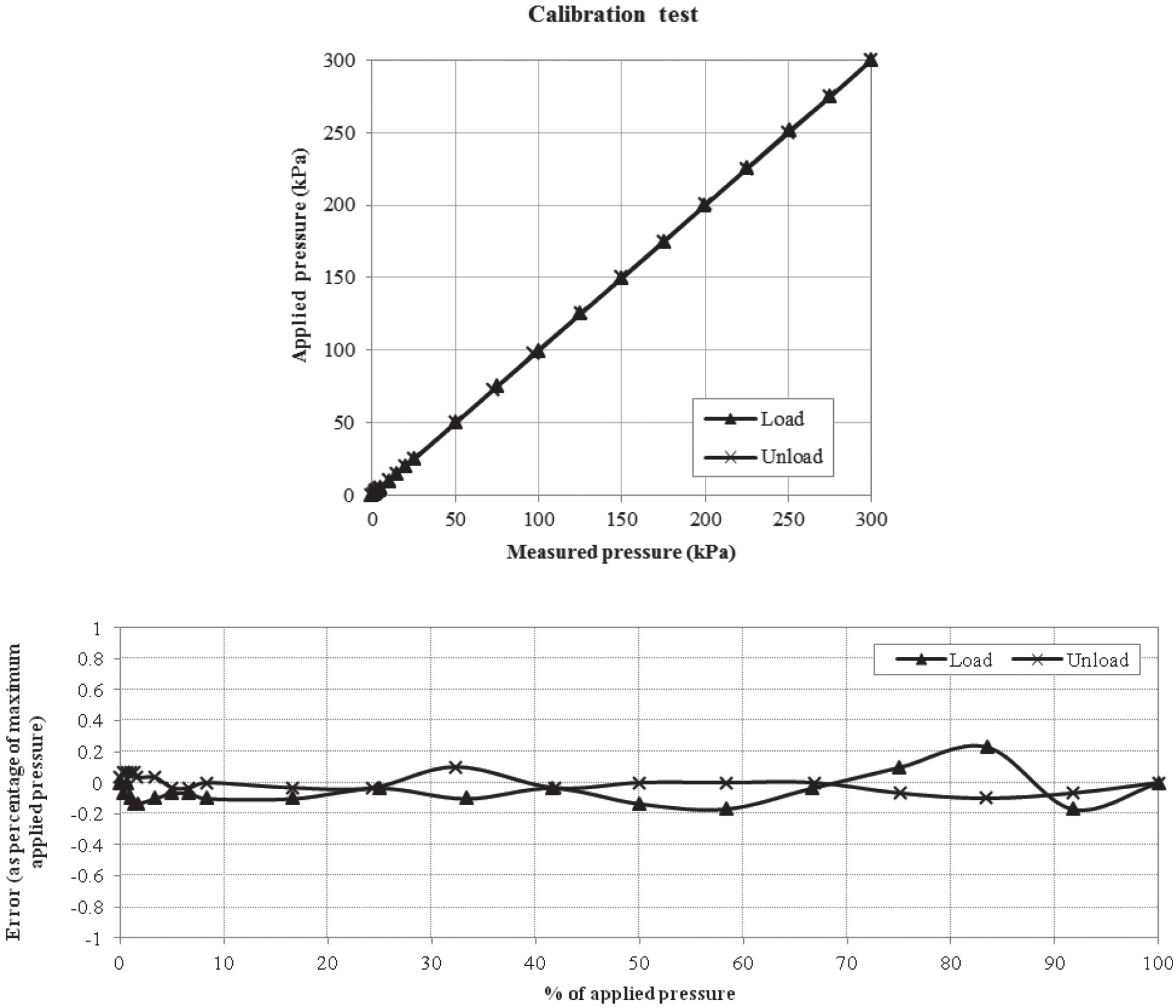

Fig. 7 – Piezocone calibration test (filter).

Fig. 7 – Calibrazione del piezocono (filtro).

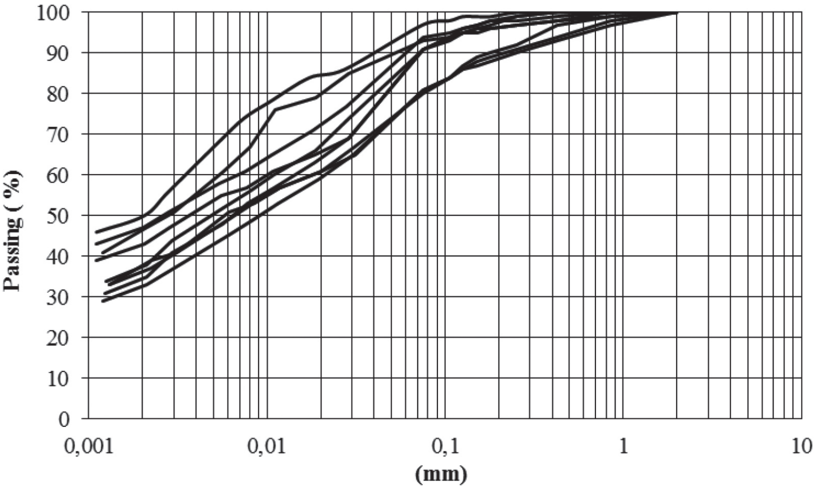

Fig. 8 – Grain size distributions for upper-soil in Broni [Meisina, 1996].

Fig. 8 – Curve granulometriche relative allo strato più superficiale a Broni [Meisina, 1996].

Tab. III – SBTn Classes [ROBERTSON, 1990].
Tab. III – Classi SBTn [ROBERTSON, 1990].

Soil classification (SBTn)	Zone number (Robertson SBT 1990)	SBT Index values
Organic soils: peats	2	$I_cI_c > 3.60$
Clays: silty clay to clay	3	$2.95 < I_cI_c < 3.60$
Silt Mixtures: clayey silt to silty clay	4	$2.60 < I_cI_c < 2.95$
Sand Mixtures: silty sand to sandy silt	5	$2.05 < I_cI_c < 2.60$
Sands: clean sand to silty sand	6	$1.31 < I_cI_c < 2.05$
Gravelly sand to dense sand	7	$I_cI_c < 1.31$

ing processes. It is possible to observe that there is a very good agreement between the measurements and applied pressures, with the absence of a threshold value, below which the transducer inside the cone would not be able to measure changes in the external pressure. Moreover, no relevant hysteresis loop can be observed. In conclusion, the slot filter saturation with grease instead of silicon oil can be considered acceptable. The use of grease is very popular in common practice, especially because the saturation procedure is much easier with grease than with oil and because the occurrence of de – saturation is more unlikely. Unfortunately, de – saturation occurred during test CPTu1 in spite of the use of grease.

The clayey nature of the deposit under consideration, and in particular of its shallower portion (first 3 meters), is shown in figures 8 and 9 and in table II. It is interesting to note that some measurements of the negative pore pressure in the laboratory, conducted by means of the filter paper method, indicated values of about 2.6 – 3.0 m [MEISINA, 1996]. These values are about half those inferred by means of the M-K model. However, it is important to recall that the soil samples were not retrieved at the same time the CPTu test was conducted.

4.2. Interpretation of CPTu

The effective vertical geostatic stresses have been re-evaluated according to the method explained in the previous section. The pore water pressure was assumed to be linear from the water table to the capillary height, h_{co} calculated with the MK model, and then constant to the surface level. For the study case, the h_{co} values are higher than the water table depth,

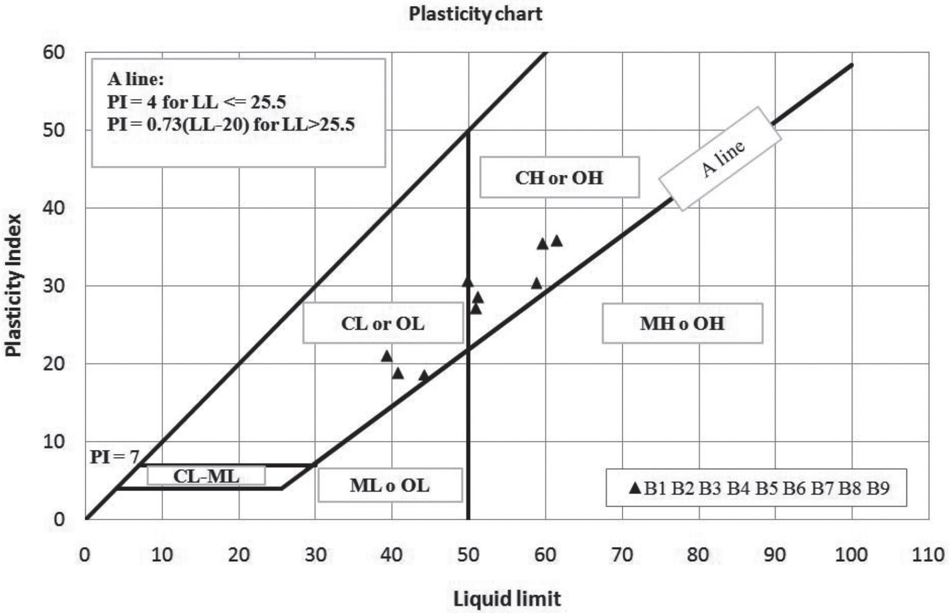

Fig. 9 – Casagrande classification chart [MEISINA, 1996].
Fig. 9 – Carta di classificazione di Casagrande [MEISINA, 1996].

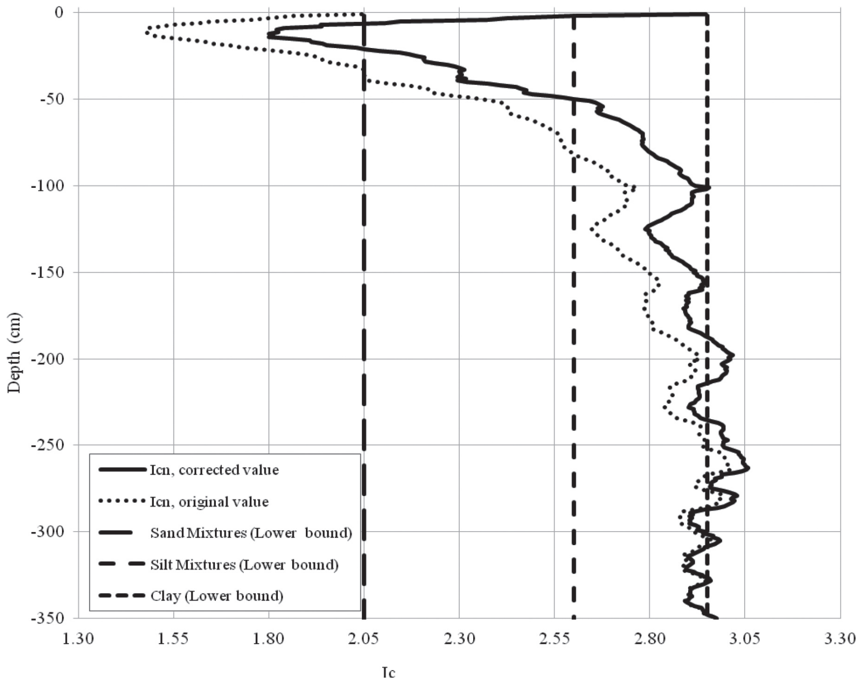

Fig. 10 – Variation of Ic values for CPTu1 (wet season).
Fig. 10 – Variazione dei valori di Ic CPTu1 (stagione umida).

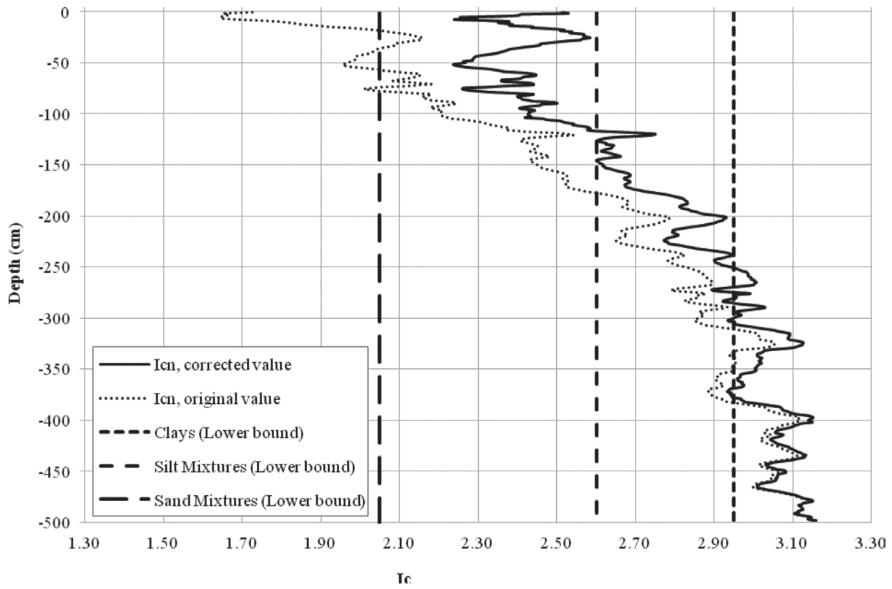

Fig. 11 – Variation of Ic values for CPTu2 (dry season).
Fig. 11 – Variazione dei valori di Ic CPTu2 (stagione asciutta).

and the pore water pressure was therefore assumed to linearly vary until the ground level. In practice, it was assumed that all the shallower portions of the subsoil were saturated by capillarity. This is in contrast with the saturation degree that was inferred from laboratory tests, as will be discussed in more detail later on.

It has been assumed that the h_{co} values are equal to Ψ_r as obtained from equation (7).

The increased values of σ'_{vo} led to a reduction in the normalized tip resistance, Q, and consequently, an increase in the Soil Classification Index I_c [ROBERTSON, 1990; ROBERTSON and WRIDE,1998], on the basis of the equations reported below and the indications summarized in table III:

$$I_c=\sqrt{(3.47-\log Q_{tn})^2+(\log(F)+1.22)^2} \qquad (10)$$

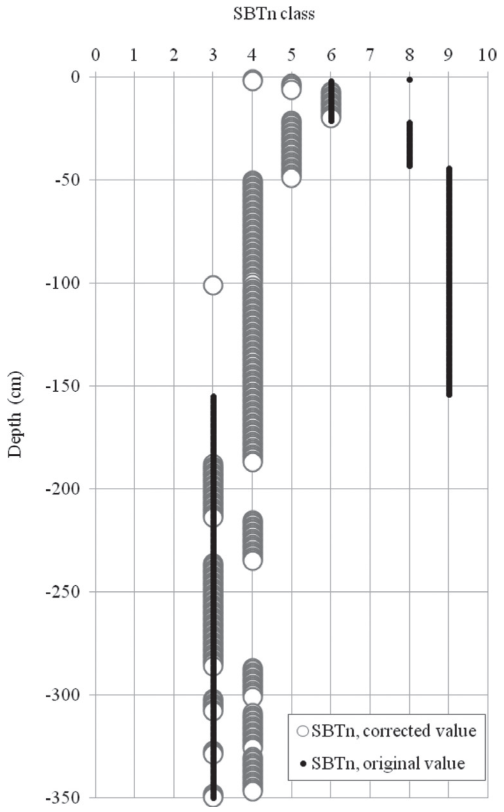

Fig. 12 – SBTn classes before and after correction for CPTu1 (humid season).

Fig. 12 – Classi SBTn prima e dopo la correzione CPTu1 (stagione umida).

$$Q_{tn}=\left(\frac{q_t-\sigma_{vo}}{\sigma_{atm}}\right)\left(\frac{\sigma_{atm}}{\sigma'_{vo}}\right)^n \quad (11)$$

$$F=\frac{f_s}{q_t-\sigma_{vo}}100 \quad (12)$$

$$n=0.381\cdot I_c+0.05\left(\frac{\sigma'_{vo}}{\sigma_{atm}}\right)-0.15 \quad (13)$$

The influence of the proposed correction on I_c is shown in figure 10 and figure 11. Such a correction moves the I_c parameter toward the target value of 3.0 (*i.e.* the I_c value that the homogeneous clay - deposit exhibits below the water table). In other words, after the correction, the target value of I_c = 3.0 is reached below the depth of 1.0 m for CPTu1 and below the depth of 2.0 m for CPTu2.

The effect of the correction on SBTn is shown in figures 12 and 13. The correction, in practice, produces an increase in SBTn classes 3 to 4 (clay to clayey silt) and completely cancels SBTn class 9 (*i.e.* very stiff fine grained soil). In other words, after the correction the SBT classification system seems to become a "Soil Type" classification. In fact the upper 5 m of the deposit is identified as fine-grained soil (SBTn classes 3 to 4), while the information on the presence of "very stiff" fine-grained soils (SBTn class 9) disappears. This information is now incorporated in the much higher values of the vertical effective stress. Therefore, it could be possible to use the proposed correction to estimate the effective in situ stress for soil layers above the water table. Figure 14 shows the vertical effective stress value for the Broni case that produces a constant I_c, which is equal to that obtained below the water table. The two different curves, shown in figure 14, have been obtained from the two considered CPTus at Broni [BUSONI, 2016; MARCONCINI, 2016]. The curves coincide with those obtained through the use of the M-K model for greater depths than 1.0 and 2.0 meters for CPTu1 and CPTu2, respectively. The thus obtained vertical effective stress could be interpreted as the result of a preconsolidation pressure induced by desiccation of the shallower layers.

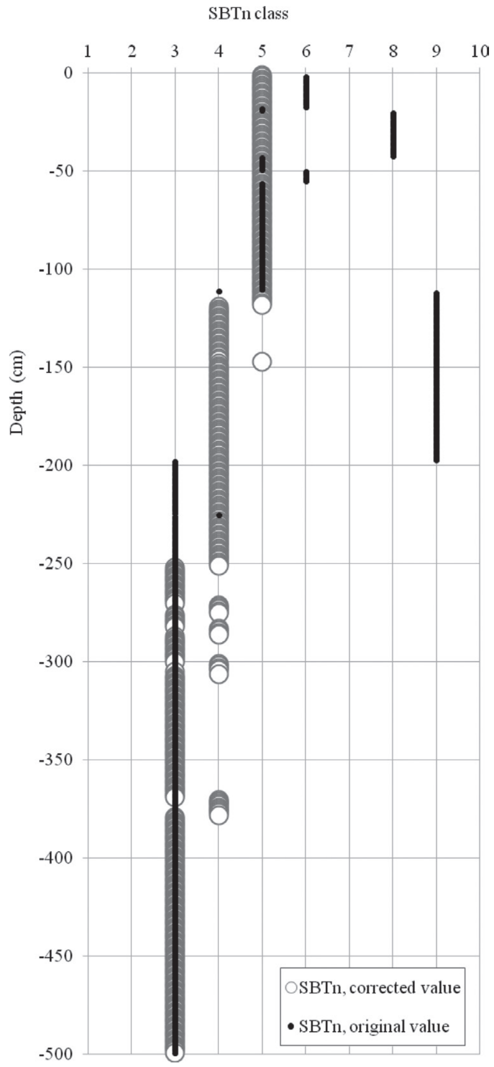

Fig. 13 – SBTn classes before and after correction for CPTu2 (dry season).

Fig. 13 – Classi SBTn prima e dopo la correzione CPTu2 (stagione asciutta).

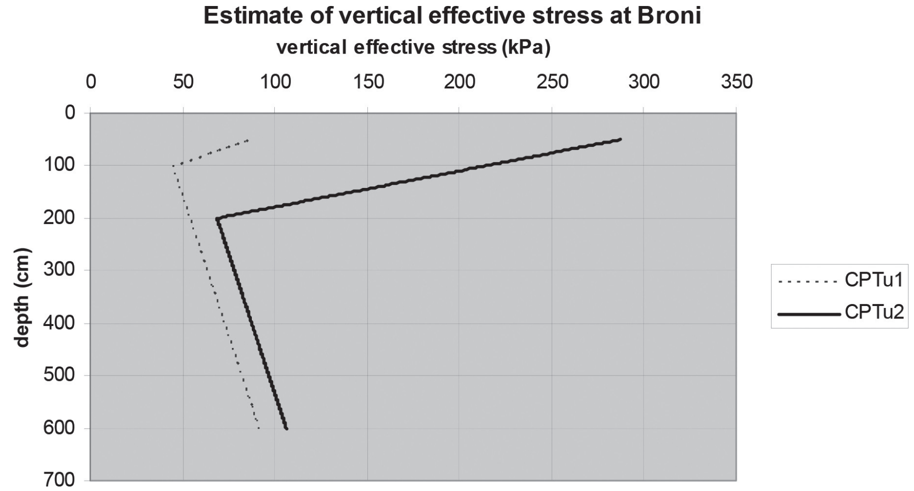

Fig. 14 – Assessment of in situ vertical stress from CPTu1 and CPTu2 (Broni).
Fig. 14 – Determinazione della tensione verticale efficace dalle prove CPTu1 and CPTu2 (Broni).

Unfortunately, this hypothesis could not be assessed for the Broni data because no laboratory tests on undisturbed samples were available. Therefore, the working hypothesis was checked by considering additional data [BARSANTI, 2016]. These data were obtained from Porcari (Lucca – Tuscany) and refer to a CPTu carried out in a partially saturated fine-grained layer (above the water table) and an oedometer test on an undisturbed sample that had been retrieved at the same location as the CPTu test from a depth of 2.0-2.3 m (Figs. 15 and 16). It can be observed that the I_c value increases with depth moving toward the target value of about 2.55, which is reached below the water table, even though in a scattered way. However, when the I_c value at a depth of 2.0 – 2.3 m (about 2.05) and the I_c target are considered, the application of the proposed method leads to an estimate of the suction

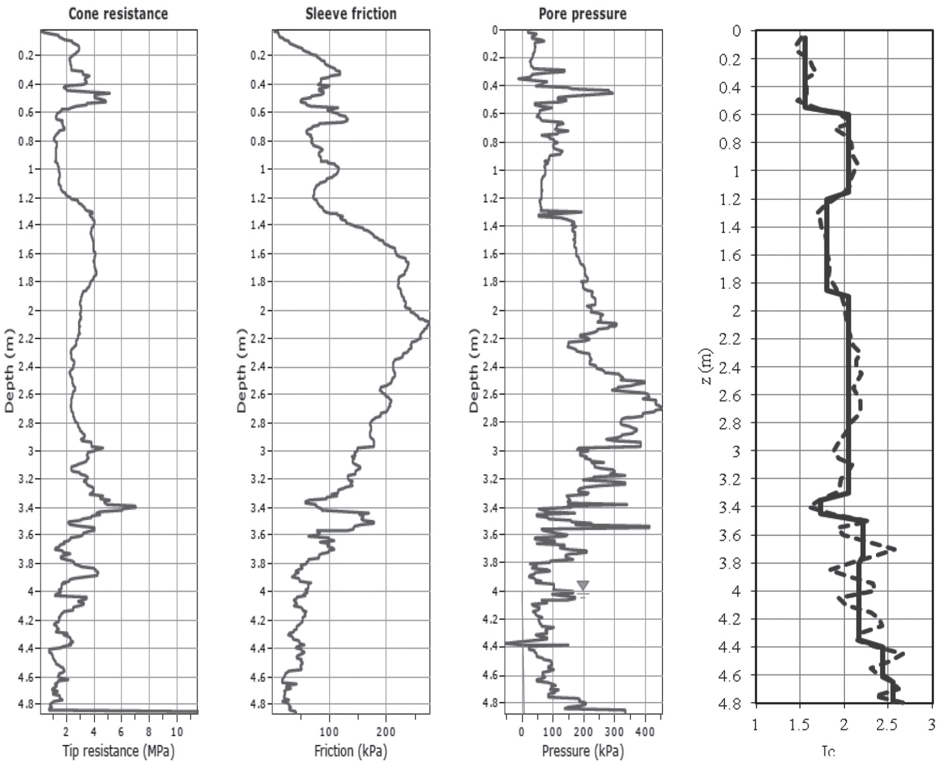

Fig. 15 – CPTu and I_c index (Porcari – Lucca).
Fig. 15 – CPTu e indice I_c (Porcari – Lucca).

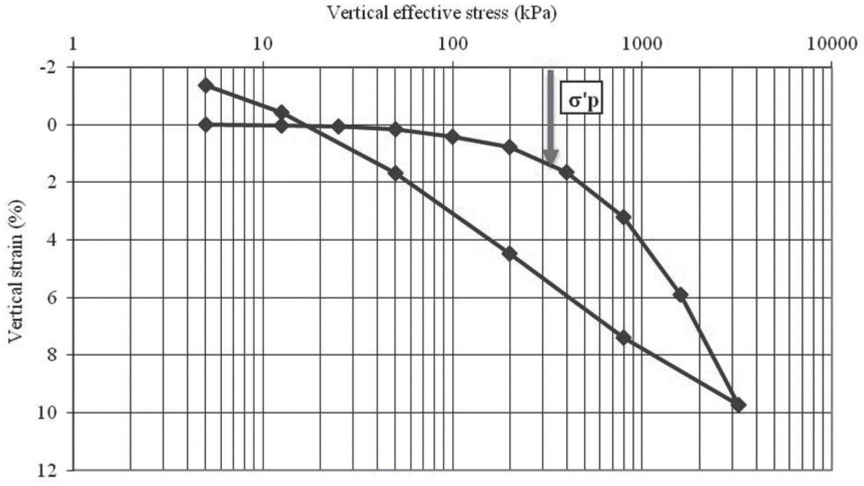

Fig. 16 – Oedometer test (Porcari Lucca).
Fig. 16 – Prova edometrica (Porcari Lucca).

of about 297 kPa. The interpretation of the oedometer test is shown in figure 16, and leads to an estimate of the preconsolidation pressure of about 320 kPa. Even though a single result cannot be considered sufficient to validate the working hypothesis, the analyzed data suggest that the proposed approach merits further investigation. The fundamental finding of this study is that the currently available classification systems have been found to be inadequate for those cases in which the effective stress state is controlled by suction. The proposed approach seems to offer the possibility of inferring the effective in situ stress state and of estimating the preconsolidation pressure. It is also worth noting the possible differences between the oedometer preconsolidation pressure and suction. The two values could only coincide when Ko =1, which is not unrealistic for highly mechanically overconsolidated soils.

5. Specific - empirical calibration of Ic vs. borehole evidence

As already mentioned this methodology is purely empirical and consists of a specific calibration of the I_c values [ROBERTSON, 1990; JEFFERIES and DAVIES, 1993], as inferred from CPTu results with evidence obtained from direct logging (boreholes). The proposed calibration is based on the following:

- the comparison was only made between the boreholes and CPTus, which were located very close to each other (maximum 1.0 m apart);
- the comparison was only made for those portions of the borehole where the grain size curve was available;
- the grain size curve was obtained and described according to AGI (1997);
- the I_c index from the CPTu was inferred by means of the CPeT-IT software [GEOLOGISMIKI, 2007];
- the I_c index from the grain size curve was established according to the indications reported in tables IV and V.

For those readers who are not familiar with the AGI (Italian Geotechnical Society) classification it is worth recalling the following rules:

- the name given to the soil is that of the main fraction;
- the expression "silt with clay" (as an example) means that there is a clay fraction of between 25 and 50%
- the expression "clayey silt" (as an example) means that there is a clay fraction of between 10 and 25%
- a fraction of less than 5% is not considered

Fractions of between 5 and 10% are shown in brackets in tables IV and V. An example is given to help understand how a correspondence between I_c and the granulometric curve has been defined. A "silt with clay" soil corresponds to SBTn class 4 with 2.60< Ic < 2.95. A more precise value of the index is assumed proportional to the percentage of clay fraction (from 25 to 50%).

It is worth recalling that the CPTu – based soil classification mainly refers to the soil behavior type (SBT), while the proposed borehole – based soil classification refers to the grain size distribution. However, one of the most relevant parameters, in the case of levees and dredged sediments as well, is the permeability which mainly depends on the grain size and degree of compaction [TATSUOKA, 2015].

Tables IV and V show the soil classification (according to AGI, 1997) and the I_c index that were selected for the various soil classes. In addition, the tables show the I_c index inferred from CPTu, the SBTn

Tab. IV – Serchio River data – I_c and classification from both CPTu and borehole – data interpretation.
Tab. IV – Dati relative al Fiume Serchio – I_c e classificazione ottenuta dall'interpretazione di prove CPTu e sondaggi.

Borehole #	**Soil classification from borehole (AGI 1997)**	**Ic from borehole**	**Ic from CPTu**	**ΔIc**	**SBTn**	**Soil classification from CPTu**
1	Clayey and sandy silt	2.60	2.79	0.19	4	Sand Mixtures
	Silty sand	2.10	2.05	-0.05	6	Sand
	Silty sand	2.10	2.49	0.39	5	Sand Mixtures
	Sand, gravel and fine gravel	1.30	1.72	0.42	6	Sand
	Silty sand	2.10	2.19	0.09	5	Sand Mixtures
2	Fine sand with silt	2.40	3.14	0.74	3	Clays
	Silty sand	2.10	2.20	0.10	5	Sand Mixtures
3	Clayey and sandy silt	2.60	1.63	-0.97	6	Sand
	Clayey and sandy silt	2.60	3.36	0.76	3	Clays
	Silty sand (5<clay<10%)	2.50	3.27	0.77	3	Clays
	Silty sand	2.10	2.85	0.75	4	Silt Mixtures
4	Silty sand	2.10	2.15	0.05	5	Sand Mixtures
	Sand, gravel and fine gravel	1.30	1.86	0.56	6	Sand
	Sand	1.70	1.93	0.23	6	Sand
	Clayey and sandy silt	2.60	3.70	1.10	2	Clay-Organic Soil
5	Sand with silt	2.50	2.74	0.24	4	Silt Mixtures
	Silt with clay	2.80	2.05	-0.75	6	Sand
	Silty sand	2.10	1.93	-0.17	6	Sand
	Sand	1.60	2.29	0.69	5	Sand Mixtures
	Silt with clay/clay with silt	3.00	3.23	0.23	3	Clays
6	Sand with silt/silt with sand	2.50	3.23	0.73	3	Clays
	Silt with clay	2.90	3.34	0.44	3	Clays
	Silty sand	2.10	3.18	1.08	3	Clays
	Clayey and sandy silt	2.60	2.99	0.39	3	Clays
	Silty sand	2.10	3.27	1.17	3	Clays
7	Silty sand	2.10	1.94	-0.16	6	Sand
	Medium silty sand	1.90	1.58	-0.32	6	Sand
	Sand, gravel and fine gravel	1.30	1.82	0.52	6	Sand
	Coarse sand (5<clay<10%)	2.00	2.06	0.06	5	Sand Mixtures
	Clayey and sandy silt	2.60	2.09	-0.51	5	Sand Mixtures
	Medium sand (5<clay<10%)	2.10	2.26	0.16	5	Sand Mixtures
	Silty sand	2.10	2.14	0.04	5	Sand Mixtures
8	Silty sand (5<clay<10%)	2.50	2.50	0.00	5	Sand Mixtures
	Silty sand	2.10	2.86	0.76	4	Silt Mixtures
	Clayey silt	2.80	3.06	0.26	3	Clays
	Sand (5<silt<10%)	2.00	3.18	1.18	3	Clays
9	Sand with silt	2.35	2.32	-0.03	5	Sand Mixtures
	Medium sand with gravel	1.40	1.73	0.33	6	Sand
	Sand (5<silt<10%)	2.00	2.95	0.95	3	Silt Mixtures
	Clayey and sandy silt	2.60	3.43	0.83	3	Sand Mixtures
	Silty sand	2.10	3.34	1.24	3	Clays
	Clayey and sandy silt	2.60	2.24	-0.36	5	Sand Mixtures
	Silty sand	2.10	2.16	0.06	5	Sand Mixtures
10	Silty sand (5<clay<10%)	2.50	3.16	0.66	3	Clays
	Silt with sand (5<clay<10%)	2.65	3.34	0.69	3	Clays
	Silty sand (5<clay<10%)	2.50	2.75	0.25	4	Silt Mixtures
	Silty sand	2.10	3.28	1.18	3	Clays
	Clayey silt	2.80	3.48	0.68	3	Clays
	Peat	3.60	3.48	-0.12	3	Clays
	Clayey silt	2.80	3.59	0.79	3	Clays
	Clayey and sandy silt	2.60	3.59	0.99	3	Clays
	Sand with silt/silt with sand	2.50	2.39	-0.11	5	Sand Mixtures
	Silty sand	2.10	2.75	0.65	4	Silt Mixtures
	Clayey silt with sand	2.55	3.73	1.18	2	Clay-Organic Soil
11	Medium to coarse sand	1.40	2.29	0.89	5	Sand Mixtures
	Clayey silt	2.80	3.64	0.84	2	Clay-Organic Soil
	Silty sand	2.10	2.79	0.69	4	Silt Mixtures
	Clayey silt	2.80	4.28	1.48	2	Clay-Organic Soil
	Medium sand (5<silt<10%)	2.00	2.73	0.73	4	Silt Mixtures
12	Medium to coarse sand	1.40	2.02	0.62	6	Sand
	Peat	3.60	4.80	1.20	2	Clay-Organic Soil
	Silt with clay	2.90	3.62	0.72	2	Clay-Organic Soil
	Clayey silty sand	2.50	3.77	1.27	2	Clay-Organic Soil
	Silt with clay	2.80	3.88	1.08	2	Clay-Organic Soil
	Silty sand	2.10	1.65	-0.45	6	Sand
	Medium to coarse sand	1.40	1.66	0.26	6	Sand Mixtures

Tab. V – Port of Livorno data – Ic and classification from both CPTu and borehole – data interpretation.
Tab. V – Dati relative al Port of Livorno – I_c e classificazione ottenuta dall'interpretazione di prove CPTu e sondaggi.

Borehole #	Soil classification from borehole (AGI 1997)	Ic from borehole	Ic from CPTu	ΔIc	SBTn	Soil classification from CPTu
SC3	Silt with sand (5<clay<10%)	2.05	3.28	1.25	3	Clays to silty clay
	Silt with clay (5<sand<10%)	2.70	3.05	0.27	3	Clays to silty clay
SC4	Silt with clay	2.75	2.92	0.13	3	Clays to silty clay
SC7	Silt with clay (5<sand<10%)	2.10	2.30	0.17	5	Sand mixture
	Silt with clay (5<sand<10%) (5<gravel<10%)	2.65	3.10	0.40	3	Clays to silty clay
SC8	Sand with silt (5<clay<10%)	1.95	2.20	0.27	5	Sand mixtures
SC14	Sandy silt with clay (5<gravel<10%)	2.10	2.36	0.22	5	Sand Mixtures
	Sandy silt with clay (5<gravel<10%)t	2.10	3.96	1.82	2	Orhanic soils
	Clayey sand with silt	1.95	2.96	0.96	3	Clays to silty clay
	Clayey sand with silt	1.95	3.12	1.30	3	Clays to silty clay
	Silt with clay (5<sand<10%)	2.10	3.36	1.27	3	Clays to silty clay
	Silt with clay (5<sand<10%)	2.10	3.64	1.55	2	Organic soils

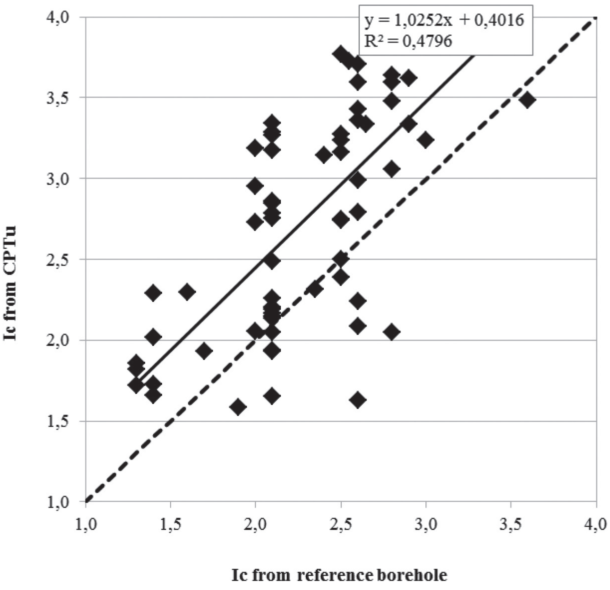

Fig. 17 – I_c values from boreholes and CPTu tests for soil layers below the water table (Serchio River area).
Fig. 17 – Valori di I_c da sondaggi e prove CPTu per strati di terreno al di sotto della falda (Serchio River area).

class number and the corresponding description. In practice, each row in tables IV and V shows the soil classification [AGI, 1997], as obtained for a homogeneous portion of borehole, and the "arbitrary" I_c value that was associated to that soil description. The term "arbitrary" I_c value refers to the fact that such an index was introduced to define an SBT and not a soil type. Both the I_c and SBTn values inferred from the corresponding CPTu at the same depth are reported in the same row. Tables IV and V only consider the soil portion below the water table. The comparison was limited to those portions of boreholes below the water table. The proposed method is intended for a user – defined correction of the classification chart.

5.1. The database of the Serchio river levee system and Livorno port

After the Serchio River flood in December 2009 in the Pisa and Lucca Districts (Italy), a huge geotechnical characterization survey was conducted in order to study the safety conditions of the embankment system and the causes that had led to its failure [COSANTI *et al.*, 2014]: boreholes, Lefranc tests, the installation of piezometers for each borehole, piezocone tests (CPTu tests), 2D Electric Resistivity Tomography (ERT) and continuous sampling (4m deep). Among these, 149 CPTu tests were conducted in the Pisa area, at various depths of between 20 and 30 meters. Of these 149 CPTu tests only 12 have been used in the present work. In fact, the above stated conditions were only met for these 12 CPTus

In recent years, there has been a great proliferation of artificial basins for the storage of dredged sediments as a result of port developments, in both Italy and the rest of the world. There is now a great deal of interest in using the same storage basins for a range of urban infrastructure projects and this requires an accurate assessment of the stratigraphy and the state of consolidation of the dredged sediments. The main goal of geotechnical engineering is to assist planning authorities with the re-use of designated dredged fill storage areas for future infrastructure projects. An excellent example is that of the Port of Livorno, where the designated 40 hectare storage basin has been filled with dredged sediments (a total vol-

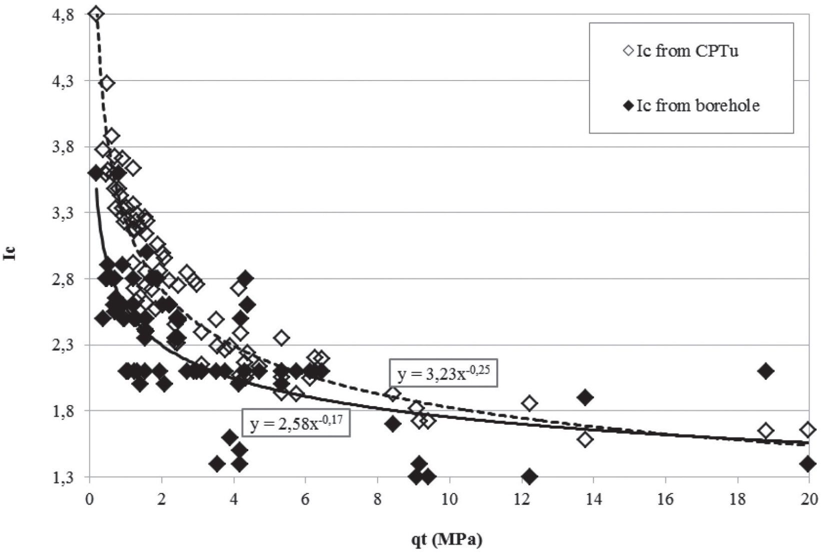

Fig. 18 – Dependency with q_t of I_c values inferred from both CPTu and boreholes (Serchio river area).
Fig. 18 – Dipendenza di q_t dai valori di I_c ricavati da prove CPTu e dai sondaggi (Area del Fiume Serchio).

ume of 1.7M m^3) since 2000. The Port of Livorno Authority has therefore carried out a huge geotechnical (and environmental) investigation campaign consisting of: a) 22 boreholes (for a total of 196.5 m); b) 18 undisturbed samples; c) 34 remoulded samples; d) 11 Lefranc (variable head) permeability tests; e) the installation and reading of 4 piezometers (open pipe); f) 26 CPTus (for a total of 153 m); g) 6 DMT (for a total of 29 m); h) laboratory tests on 50 different samples. A comparison has only been made considering 12 CPTus, and only for those portions of subsoil for which the grain size curve was available.

5.2. Empirical Ic correction

The diagram in figure 17 displays the values of I_c obtained from the CPTu tests (Serchio River area) and from the corresponding boreholes for soil layers below the water table. The differences between the two values are particularly evident for SBTn classes 3, 4 and 5, in which I_c varies between 1.90 and 3.22. In particular, it is possible to observe an almost systematic bias between the two series of values. The dependence of the Soil Classification Index, I_c on the total tip resistance, q_t, is shown in figure 18 (Serchio River area). Figure 18 shows the I_c values obtained from both the CPTu and from borehole data interpretation. The values obtained from the CPTus are generally higher, while those inferred from boreholes are lower (Tab. IV). As the total tip resistance increases, the differences between the two series become negligible, and, from a practical point of view, not very relevant.

The difference between the two I_c series (ΔI_c) is plotted vs. the total tip resistance in figure 19 (Serchio River and Port of Livorno areas). The best fit of such data is given by the following equation [ROSIGNOLI, 2014; FULCINITI, 2016].

$$\Delta I_c = 0.05 + \frac{0.75}{q_t} \qquad (14)$$

q_t (MPa)

The $\Delta I_c(q_t)$ function was used to correct the CPTu interpretation (Serchio river data). The new results, after the correction, are shown in figure 20. It is possible to observe that the dispersion of the corrected data is much lower than that of the original values. Moreover, the I_c values are arranged better around the 45° angle line, thus leading to a much better correspondence between the SBTn classes identified from the CPTu tests and those inferred from the boreholes (based on grain size).

The proposed correction is only applicable to the considered soils and the analyzed database. The proposed correction in fact depends on the tip resistance, and becomes particularly relevant for resistances below 1 MPa. On the other hand, the ROBERTSON [1990] classification – system has been applied successfully to obtain the soil stratigraphy of soft deposits with tip resistances of less than 1 MPa.

The Robertson [1990] classification-system has been applied successfully by the Authors, without any correction, for the interpretation of tests in the Arno River area (near the city of Pisa). These sediments mainly consist of [LO PRESTI *et al.*, 2002]:

- recent (Holocene) fluvio – lacustrine and silting deposits (sometimes with organic soil). These sediments are heterogeneous and mainly consist of silty-clayey soil, often containing archaeological remains;

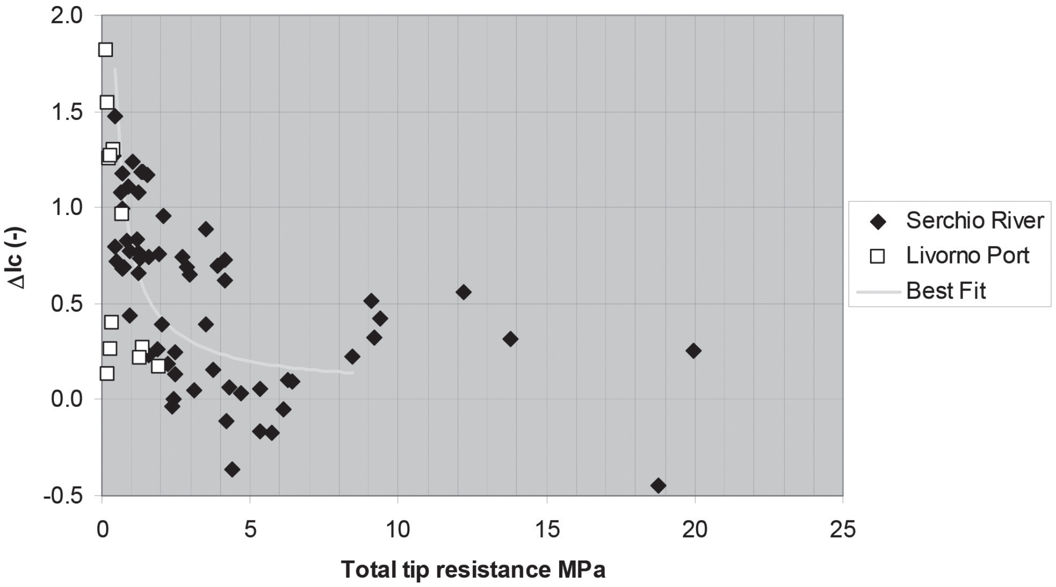

Fig. 19 – The difference between the two Ic series (ΔIc) vs. the total tip resistance.
Fig. 19 – Differenze tra le due serie di Ic (ΔIc) in funzione della resistenza alla punta totale.

– (Holocene) soft marine clay deposits

Therefore, an attempt has been made to distinguish the silt mixtures of the Serchio River (qt < 1 MPa) from the soft marine clay or organic clay and silt of the Pisa valley (qt < 1 MPa).

To this aim, a large database of CPTu tests, performed within the city of Pisa, has been used [COSCO and SPADARO, 2014; ZACCAGNINO, 2014; SCARDIGLI, 2014; PONZANELLI, 2014]. Penetration resistance and sleeve friction (only when qt < 1 MPa) were considered. Boreholes and laboratory testing were also performed but, unfortunately, this information was not available to the Authors. Therefore, the nature of the tested soils *(i.e.* clay and organic clay) has only been assumed on the basis of geological evidence.

Figures 21a and 21b show the classification of the Serchio River sediments and that of the Pisa valley sediments according to ROBERTSON [1990]. Figure 21 does not point out too many differences between the two types of soil. On the other hand, clear differences can be observed when figures 22a and 22b are compared. These figures show the frequency distribution of the friction ratio for the considered database. It is evident that while most of the Rf values for the Serchio River sediments are equal or less than 4% (only 15% of the data has Rf > 4 %), about 50 to 60 % of the Pisa valley sediments exhibit an Rf > 4 %. It is worth recalling that the Serchio River sediments are mainly silts with intermediate permeability as inferred from boreholes and laboratory testing. The presence of clayey silts for the considered database is limited to only a very few cases that can be identified. On the other hand, the clayey nature of the Pisa valley sediments has only been hypothesized. At the same time, it is not possible to exclude the presence of other silty layers in the database concerning the Pisa valley sediments.

In the absence of more detailed information, it is not possible to draw more precise conclusions, but simply reconfirm the very old and well - known criterion which indicates an Rf > 4% for very soft and organic clays.

6. Conclusions

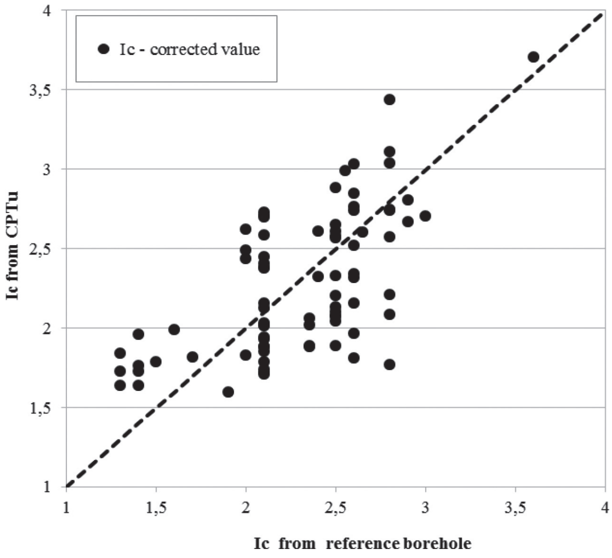

Fig. 20 – Comparison of Ic indexes from CPTu and boreholes after the proposed correction (Serchio river area).
Fig. 20 – Confronto dei valori dell'indice Ic da prove CPTu e sondaggi dopo la correzione proposta (Area del Fiume Serchio).

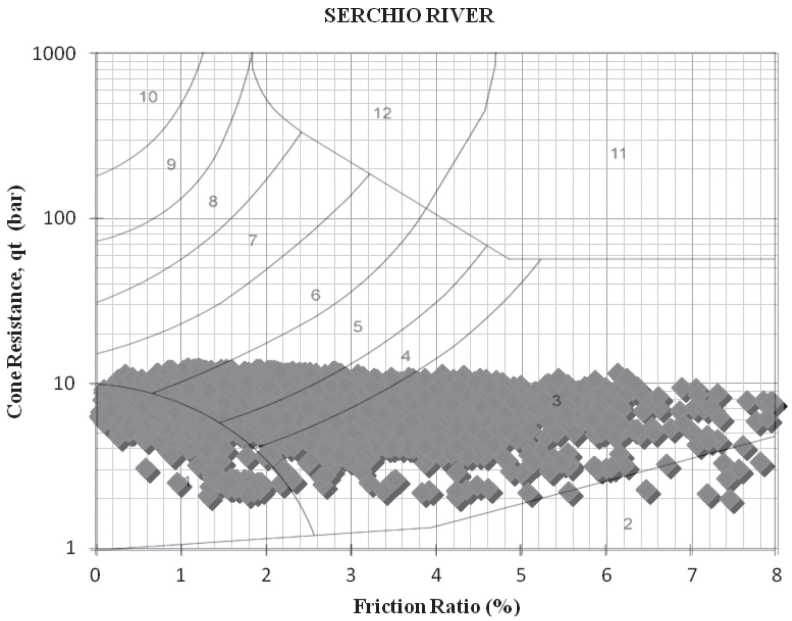

Fig. 21a – SBTn Serchio River.
Fig. 21a – SBTn (Fiume Serchio).

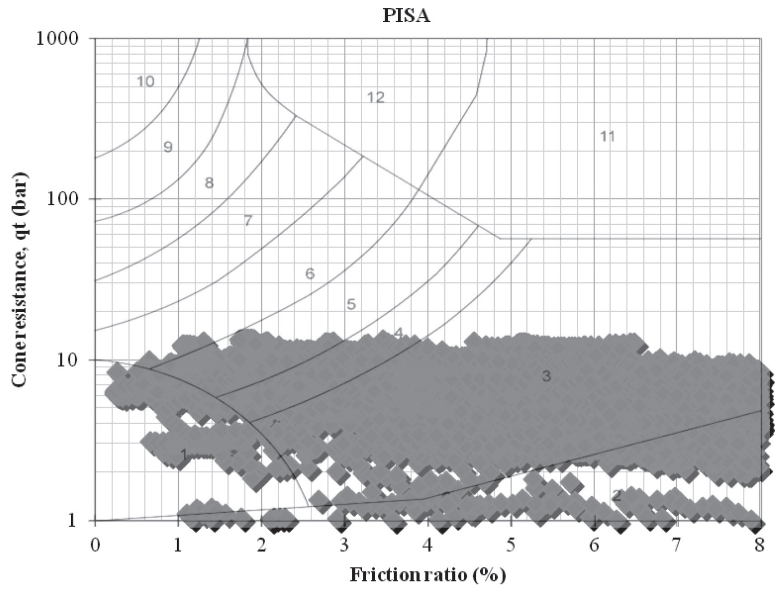

Fig. 21b – SBTn Pisa clayey sediments.
Fig. 21b – SBTn (Sedimenti argillosi – Pisa).

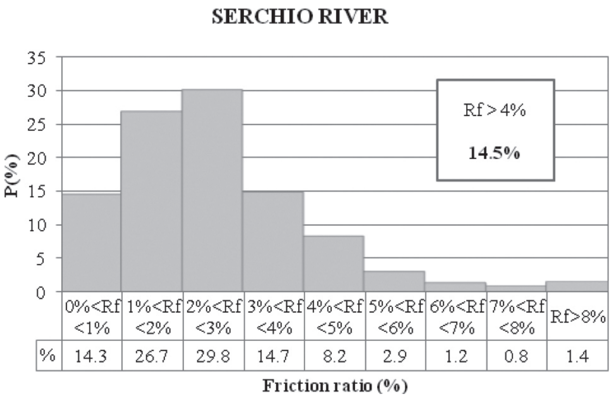

Fig. 22a – Rf distribution of Serchio River Levees.
Fig. 22a – Distribuzione di Rf (Rilevati del Fiume Serchio).

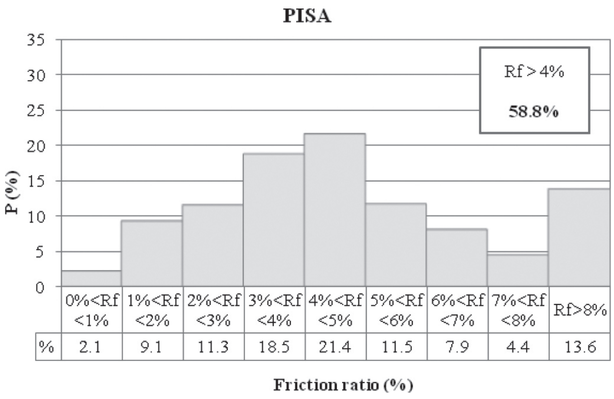

Fig. 22b – Rf distribution of the Pisa clayey sediments.
Fig. 22b – Distribuzione di Rf (Sedimenti argillosi – Pisa).

The shown data allow the following conclusions to be drawn:

- the use of the currently available classification systems is not recommended for soil layers above the water table (suction controlled) or for very loose silt mixtures;
- the paper shows the possibility of estimating the effective stress state in the vadose zone by increasing (at various depths) the negative pore pressure until the I_c index matches that measured below the water table. This approach requires further verifications. Moreover, it is only applicable to homogeneous layers;
- the empirical correction of the I_c index is only applicable to the studied cases, but the proposed methodology could be extended to other contexts. This approach guarantees the possibility of continuing to use the currently available commercial program for CPTu interpretation

Acknowledgements

Thanks are due to Mrs. Marguerite Jones for reviewing the paper from an English point of view. The Authors would also like to thank Mr. P. Barsanti, Mr. M. Cosco, Mr. F. Spadaro and Prof. C. Meisina for having supplied the data.

References

AGI (1997) – *Raccomandazioni sulle Prove Geotecniche di Laboratorio.* http://www.associazionegeotecnica.it/pubblicazioni/raccomandazioni. 56pp

Aubertin M., Mbonimpa M., Bussière B., Chapuis R. P. (2003) – *A model to predict the water retention curve from basic geotechnical properties.* Canadian Geotechnical Journal, n. 40, pp. 1104-1122.

Aubertin M., Ricard J.-F., Chapuis R.P. (1998) – A *predictive model for the water retention curve: application to tailings from hard-rock mines.* Canadian Geotechnical Journal, 35, pp. 55-69 (with Erratum, 36, 401)

Begemann H.K.S. (1965) – *The Friction Jacket Cone as an Aid in Determining the Soil Profile.* Proc. 6th ICSMFE, 1, pp. 17-20.

Bellotti R., Crippa V., Pedroni S., Ghionna V.N. (1988) – *Saturation of Sand Specimen for Calibration Chamber Tests.* Proc. ISOPT-1, Orlando, 2, pp. 661-672.

Barsanti P. (2016) – *Indagini Geotecniche in Località Porcari (Lucca).* Personal Communication to the first Author.

Busoni D. (2016) – *Procedura innovativa per la determinazione dell'OCR da prove CPTu in terreni parzialmente saturi.* B.Sc. Thesis University of Pisa.

Cosanti B., Squeglia N., Lo Presti D.C.F. (2014) – *Analysis of existing levee systems: the Serchio river case.* Rivista Italiana di Geotecnica, n. 4, pp. 47-65.

Cosco M., Spadaro F. (2014) – *Database of CPTu in the Pisa Area.* Personal communication to the first Author

Douglas J.B., Olsen R.S. (1981) – *Soil Classification Using Electric Cone Penetrometer.* Symposium on Cone Penetration Testing and Experience, Geotechnical Engineering Division, ASCE, St. Louis, pp. 209-227.

Elmgren K. (1995) – *Slot-Type Pore Pressure CPTu Filters.* Proc. Int. Symposium on Cone Penetration Testing, Swedish Geotechnical Society Report, n.3, 95, Linköping, Sweden, n.2, pp.9-12.

Eslami A., Fellenius B.H. (1997) – *Pile Capacity by Direct CPT and CPTu Methods Applied to 102 Case Histories.* Can. Geotech. J., n.34, pp. 886-904.

Fulciniti N. (2016) – *Interpretazione della prova penetrometrica statica (CPT) su terreni parzialmente saturi e comprimibili (sedimenti di colmata).* B. Sc. Thesis University of Pisa

Geologismiki (2007) – *Geotechnical Software, CPeT-IT v 1.6.* CPT interpretation software, http://www.geologismiki.gr/Products/CPeT-IT.html.

Jamiolkowski M., Lo Presti D. C. F., Manassero M. (2001) – *Evaluation of Relative Density and Shear Strength of Sands from CPT and DMT.* Invited Lecture Ladd Symposium, GSP n.119, ASCE, pp. 201-238.

Jefferies M.G., Davies M.P. (1993) – *Use of CPTu to Estimate Equivalent SPT N60.* Geotechnical Testing Journal, vol. XVI, n. 4, pp. 458-468.

Kovács G. (1981) – *Seepage Hydraulics.* Elsevier Science Publishers, Amsterdam.

Larsson R. (1995) – *Use of a Thin Slot as Filter in Piezocone Tests.* Proc. Int. Symposium on Cone Penetration Testing, Swedish Geotechnical Society Report, 3, n. 95, Linköping, Sweden, 2, pp.35-40.

Lo Presti D., Jamiolkowski M., Pepe C. (2002) – *Geotechnical Characterization of the Subsoil of the Pisa Tower.* Invited Lecture International Workshop on Characterization and Engineering Properties of Natural Soils (National University of Singapore, Dec. 2002), Balkema, vol. II, pp. 909-946.

Lo Presti D., Meisina C., Squeglia N. (2009) – *Applicabilità di prove penetrometriche statiche nella ricostruzione del profilo stratigrafico* Rivista Italiana di Geotecnica, n. 2, pp.9-33.

Marconcini M. (2016) – *Procedura Innovativa per la Determinazione dei parametri di Resistenza da Prove CPTu in Terreni Parzialmente Saturi.* B. Sc. Thesis, University of Pisa.

Mbonimpa M., Aubertin M., Chapuis R.P., Bussière B. (2000) – *Développement de fonctions hydriques utilisant les propriétés géotechniques de base.* Proc. 1st Joint IAH-CNC and CGS Groundwater Specialty Conference, 53rd Canadian Geotechnical Conference, Montreal, Quebec, Canada, pp. 343-350.

Mbonimpa M., Aubertin M., Chapuis R.P., Bussière B. (2002) – *Practical pedotransfer functions for estimating* *the saturated hydraulic conductivity*. Geotechnical and Geological Engineering.

Meisina C. (1996) – *Criteri e metodi per la valutazione della capacità di rigonfiamento di alcuni terreni e suoli affioranti nel territorio pavese.* Tesi di Dottorato in ricerca in Scienze della Terra, VIII° ciclo, Università di Pavia.

Ponzanelli M. (2014) – *Ricostruzione del profilo stratigrafico tramite prove penetrometriche statiche.* B. Sc. Thesis University of Pisa.

Robertson P. K., Campanella R. G., Gillespie D., Grieg J. (1986) – *Use of Piezometer Cone Data.* Proc. ASCE, Geotechnical Special Publication GSP n. 6, pp.1263-1280.

Robertson P.K. (1990) – *Soil classification using the cone penetration test.* Canadian Geotechnical Journal, n.27, pp. 151-158.

Robertson P.K., Wride C.E. (1998) – *Evaluating Cyclic Liquefaction Potential Using the Cone Penetration Test.* Canadian Geotechnical Journal, vol. XXXY, n.3, pp.442-459.

Rosignoli L. (2014) – *Uso della Prova Penetrometrica Statica (CPT) nelle Analisi di Stabilità dei Pendii.* M. Sc. Thesis. University of Pisa.

Scardigli A. (2014) – *Interpretazione della prova penetrometrica statica in terreni comprimibili (argille e torbe).* B. Sc. Thesis University of Pisa.

Schmertmann J.H. (1976) – *An Updated Correlation between Relative Density DR and Fugro-Type Electric Cone Bearing, qc.* Contract Report DACW 39-76 M 6646 WES, Vicksburg, Miss., 1976

Schmertmann J.H. (1978) – *Guidelines for cone penetration test performance and design.* US Dept. of Transportation, FHWA, R.78-209. Washington D.C.

Searle J.W. (1979) – *The Interpretation of Begemann Friction Jacket Cone Results to Give Soil Types and Design Parameters.* Design Parameters in Geotechnical Engineering, BCS London. 2, pp. 265-270.

Tatsuoka F. (2015) – *Compaction Characteristics and Physical Properties of Compacted Soil Controlled by the Degree of Saturation. Proc.* Sixth International Symposium on Deformation Characteristics of Geomaterials. Buenos Aires, Nov. 2015.

Zaccagnino C. (2014) – *Interpretazione della prova penetrometrica statica (CPT) su terreni parzialmente saturi e comprimibili.* B. Sc. Thesis University of Pisa.

Interpretazione di prove CPTu in terreni atipici

Sommario

Il lavoro riguarda l'interpretazione delle prove CPTu eseguite in terreni inusuali come quelli sopra falda, influenzati dalla suzione, o i terreni di intermedia permeabilità allo stato sciolto.

Per i terreni sopra falda l'articolo mostra un possible approccio per ricavare la tensione verticale efficace (comprensiva della suzione) dall'indice I_c*. Questo approccio è stato verificato rispetto ad un numero molto limitato di evidenze sperimentali. Il metodo consiste nel correggere il valore dell'indice incrementando arbitrariamente a diverse profondità il valore della pressione interstiziale (negativa) in modo da ottenere un incremento della tensione efficace. L'obiettivo è quello di ottenere un valore dell'indice corrispondente a quello misurato sotto falda. Il metodo può essere applicato a strati omogenei. Viene avanzata l'ipotesi che la tensione così determinata rappresenti la tensione di preconsolidazione.*

Inoltre viene fornita una correzione enpirica dell'indice Ic, applicabile solamente ai casi di studio. La metodologia seguita può essere replicata e calibrata in situazioni differenti.

La correzione offre il vantaggio di poter continuare a interpretare le prove CPTu utilizzando i software comunemente utilizzati.