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Empirical correlations to improve the use of mechanical CPT in the liquefaction potential evaluation and soil profile reconstruction

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ABSTRACT: CPT-based simplified methods are the common used approaches to determine the liquefaction hazard and they require cone penetration test with electrical tip. However, in some countries, as Italy, penetrometric tests are carried out with mechanical tip (CPTm). The cone—shape effects on sleeve friction (fs) have the greatest influence on soil classification in terms of SBT, underestimating the grain size of loose soils (e.g. sands) with respect to CPTu. An empirical correlation between the fs measured with CPTm and CPTu was tested. Moreover, another correlation was developed to determine a ΔIc value as function of the cone resistance in the case of silty sands and sandy silts non correctly identified by the SBT classification systems. The correlation was applied to tests carried out in the area interested by the 2012 Emilia earthquake (Italy), where liquefaction phenomena have occurred. The procedure makes possible to use huge existing database (CPTm) for liquefaction risk assessment.

1 INTRODUCTION

Liquefaction mainly occurs in saturated sandy soils and causes the loss of shear strength, which in turn leads to an almost complete loss of bearing capacity. As a consequence, the structures experience high differential settlements, tilting, or overturning. Eventually, in the free field conditions, sand ejection and pore water pressure increase can damage infrastructures and lifeline systems. Recent examples of these effects include damage produced during the 2012 Emilia and 2010–2011 Canterbury earthquakes (Lo Presti et al. 2013; Bray et al. 2014). The identification of the area prone to liquefaction is therefore an important task for land use planning. It provides to decision makers useful information about site-specific geotechnical investigation and the identification of areas requiring ground improvement.

The most known methods for liquefaction hazard assessment are simplified empirical (or semi—empirical) procedures (Liquefaction Evaluation Procedures—LEPs) (Seed & Idriss 1971; Boulanger & Idriss 2014; Robertson & Wride 1998).

Simplified procedures evaluate the liquefaction potential of soils computing the factor of safety (FSL) against liquefaction at a given depth in the soil profile and consist of two steps: 1) Evaluation of the earthquake-induced shear stress through an estimate of the cyclic stress ratio (CSR) (Seed & Idriss, 1971) and 2) Evaluation of the soil strength to liquefaction usually accomplished through an estimate of the cyclic resistance ratio (CRR). Because of the difficulty of sampling, CRR is generally determined via in situ tests, such as standard penetration test (SPT) (Seed & Idriss 1971; Youd et al. 2009), cone penetration test (CPT) (Idriss & Boulanger 2006; Robertson & Campanella 1985; Juang et al. 2003), shear wave velocity (Vs) (Andrus & Stokoe 2000), flat dilatometer tests (DMTs), and self-boring pressuremeter (SBPT). Once the safety factor against liquefaction has been computed at various depths, numerical indicators or qualitative criteria to define the liquefaction severity at ground level can be used such as the LPI index (Iwasaki et al. 1978) or the LSN parameter (Tonkin & Taylor 2013).

CPT based LEPs were developed with reference to the results of electrical tests (i.e. cone tests with piezocone). On the other hand, in some countries, as Italy, huge databases of cone tests with mechanical tip (CPTm) are available.

The different equipment of CPTm and electrical CPT lead to differences between the two typologies of tests. While the cone—shape effects on tip resistance (qc) are not very relevant, those on the sleeve friction (fs) can strongly influence the FSL calculation, especially in the case of silty sands; fs measured with the mechanical tip is always greater than the one measured with the electrical tip (the difference is practically negligible for clay). The use of classification methods which were developed to interpret CPTu, mainly causes the lack of identification of sandy to silty liquefiable layers.

Meisina et al. 2017 developed a relationship establishing empirical correlation between the sleeve friction measured with mechanical tip and that measured with electrical cone (piezocone) in order to correct CPTm results. The authors compared the SBT classes, evaluated according to Robertson 1990, to that given by Schmertmann (1978) classification chart for a large CPTm database. They found an empirical correction of the Ic index (Soil Behaviour Type Index), so that the Robertson SBT class coincide with that of Schmertmann (1978).

The aim of the paper was to apply corrections of fs and Ic proposed by Meisina et al. 2017 to CPTm in order to verify the effectiveness of the proposed methodology in 1) liquefiable layers identification; 2) build subsoil model for liquefaction hazard assessment.

Table 1. Correspondence between Schmertmann (1978) and Robertson (1990) approaches (classes 1 and 9 of Robertson approach were not considered).

Schmertmann (1978)	SBTn (Robertson 1990)
Organic clay and mixed soils	2
Insensitive non fissured inorganic clays	3
Sandy and silty clays	4
Clayey sands and silts	5
Silt—sand mixtures	5
Sands	6–7
Dense or cemented sands	8
Very shell sands, limerocks	8

2 MATERIALS AND METHODS

2.1 *Materials*

Pairs of text CPTm and CPTu not used for the development of the correlation of Meisina et al. (2017) were analysed. They were carried out in the Po Plain in Northern Italy and belong to the database of the Emilia Romagna region interested by the seismic sequence of May–June 2012 (Regione Emilia Romagna 2011). This seismic sequence is an example of a moderate earthquake yielding the most prominent extensive liquefaction phenomena of the last century in Italy (Emergeo Working Group 2013). Liquefaction related phenomena and associated ground failures caused damages and extensive problems mainly to infrastructures (roads, wells, lifelines, etc.) while the foundation system of very few buildings was damaged. Most of the liquefaction sites are located on elevated fluvial ridges.

2.2 *Methods*

Using the results of the tests that have been carried out at Pisa (Central Italy) and those of four pairs of CPTm/CPTu from Emilia-Romagna Region database (2011), a correlation function between the fs(CPTm) and the fs(CPTu) was found by Meisina et al. 2017.

The measured sleeve friction is corrected according to the following equations

$$fs(CPTu) = [0{,}0797\, fs(CPTm)]^{2.504} \quad (1)$$

if fs(CPTm) < 65 kPa

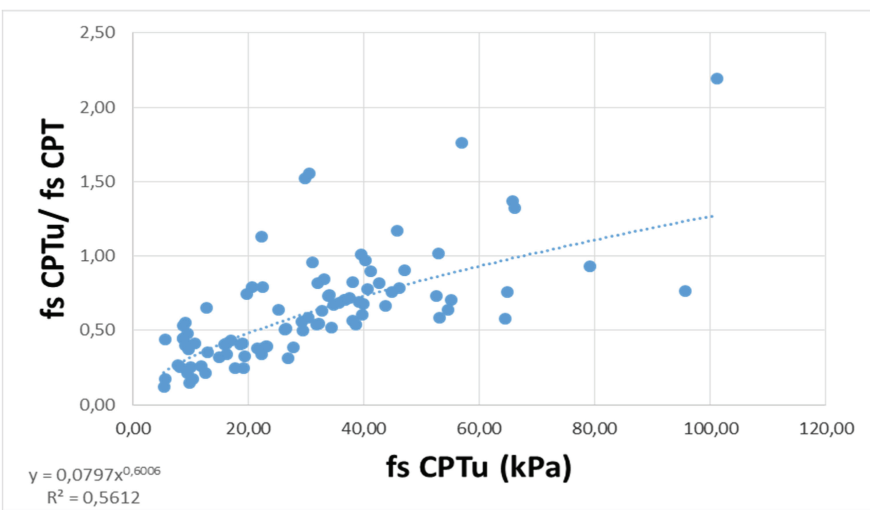

Figure 1. Correlation function between fs(CPTm) and fs(CPTu).

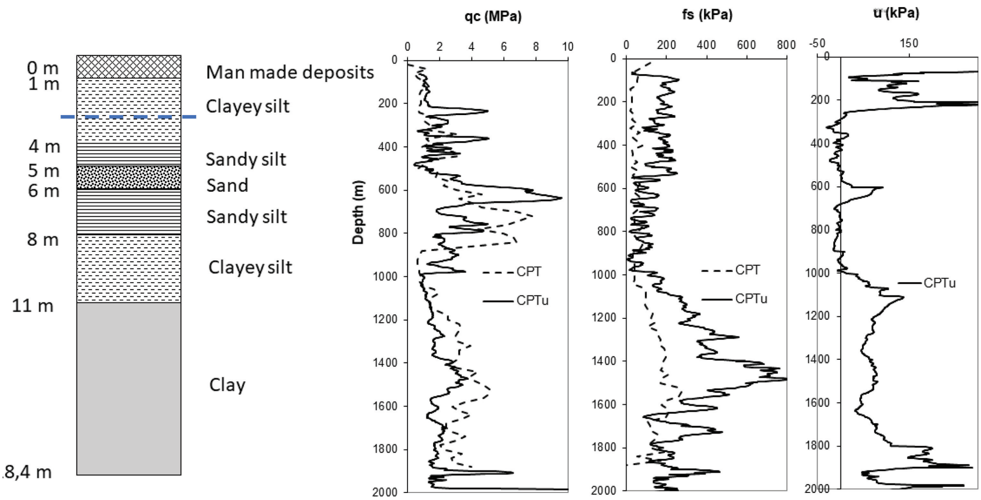

Figure 2. Case history 1. Simplified borehole, CPTm and CPTu qc, fs and u.. In blue the Ground Water Table.

$$fs(CPTu) = fs(CPTm) \qquad (2)$$

if fs(CPTm) > = 65 kPa.

The Ic index is also corrected according to the following equation:

$$\Delta Ic = -0.296 \ln(qc) + 0.8568 \qquad (3)$$

$$Ic\ (correct) = Ic(Robertson,\ 1990) - \Delta Ic \qquad (4)$$

The correction was obtained by comparing soil classes of the Schmertmann (1978) approach to those inferred by using the Robertson (1990) SBTn (Tab. 1). Mainly the use of Robertson (1990) for interpreting CPTm leads to an underestimate of soil granulometry. The proposed correction applies only when the Robertson (1990) classification underestimate that of Schmertmann (1978b).

Normalized class description: 2: Organic soils, peats; 3: Clays: clay to silty clay; 4: silt mixtures: clayey silt to silty clay; 5: Sand mixtures: silty sand to sandy silt; 6–7: Sands: clean sand to silty sand; Gravely sands to sands; 8: Very stiff sand to clayey sand; Very stiff sand to clayey sand.

3 RESULTS

3.1 *Application of the developed methodology*

The methodology of correction was applied to different pairs of tests CPTm-CPTu, representative of the following conditions:

a. Level of sand interbedded within layers of sandy silt (Case history 1);
b. Level of sandy silts and silty sand (Case history 2).

The liquefiable layers consist on sand and silty sand with FC (materials passing a number 200 sieve ASTM) = 18–28%.

The pairs CPTm and CPTu are at a distance less than 100–200 m from liquefaction phenomena (sand boils). They have a relative distance of 50–30 m. For each pair of test a reference borehole, with a maximum distance of 9–50 m from the considered CPT, was selected in order to define a reference stratigraphic profile. The area is characterized by a strong lithological heterogeneity. Nevertheless, the pairs of tests and the reference borehole were selected so that they belong to the same geomorphologic unit and have therefore the same behavior with respect to liquefaction.

The first step consisted in the borehole simplification in order to obtain simplified soil profiles allowing to identify the critical layers responsible for liquefaction.

In a second step for each layer Ic (normalized soil behavior index) values are calculated following the method of Robertson, 1990. It was assumed that liquefiable soils are characterized by Ic < = 2.6 (Cubrinovski et al. 2017). Factors of safety against liquefaction were computed according to the procedures proposed by Boulanger & Idriss (2014) method.

For the interpretation of CPTm and CPT the software CPT PaGE, developed by University of Pisa, was used (Stacul et al. 2017).

3.2 *Case history 1*

The stratigraphy of the subsoil is characterized by non liquefiable layers (clayey silt and silt and clay) in the first 4 m. The potential critical layers for soil liquefaction develop between 4 and 8 m and it is constituted by silty sand (4–5 m), sand (5 to 6 m), followed by two meters of sandy silt (Fig. 2). Clayey silt and clay are present till 18 m followed by sandy silt. The depth to the water table is 3.5 m.

Differences of qc and fs can be also related to local heterogeneity of the soil stratigraphy (Fig. 2).

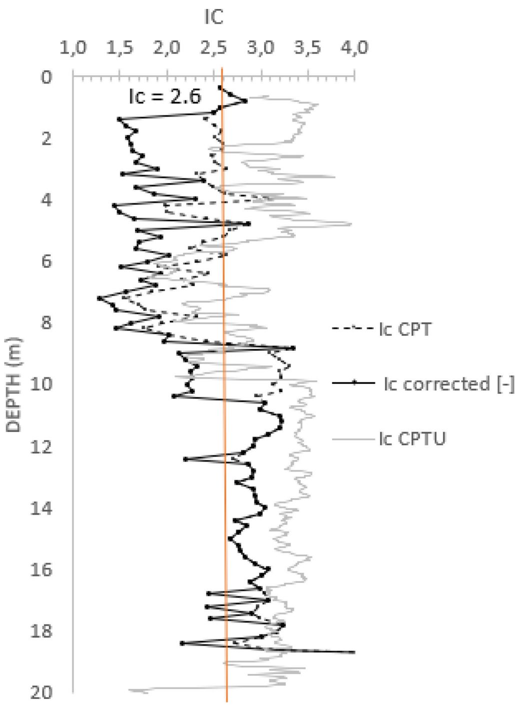

Figure 3. Case history 1. Ic variation with depth.

The Ic, calculated through CPTu, assumes values generally greater than 2.6, except for the layer of sand (5–6 m) for which $1.8 < Ic < 2.55$.

In the CPTm the most surficial sandy silt layer has non corrected Ic values from 2.1 and 2.6, for the sand Ic ranges between 1.9 and 2.45; meanwhile the deeper sandy silt layer presents values from 1.62 and 2.02 (Fig. 3).

The CPTu test identify liquefiable horizons between 5–6 m (sand).

The Ic values calculated through CPTm indicate that for mechanical penetrometric test the liquefiable horizon is thicker and includes also sandy silt and silty sand.

The application of the correction for CPTm further reduces the values of Ic, which are always lower than 2.1 (from 1.3 to 1.9 for the sandy layer).

In this case the Ic seems to be underestimated especially for soils between 8 and 10 meters. This lead to evaluate as prone to liquefaction clay and silty soils.

3.3 *Case history 2*

The subsoil is composed by the alternation of silty sand and sandy silt and silty sand till 8.8 m overlying clayey silt (Fig.4).

The depth to the water table is 2.7 m.

Ic calculated though mechanical CPTm in the interval 3.1 to 8.8 m ranges between 1.98 and 2.55 (Fig.5).

For CPTu Ic is greater than 2.6 except between 3.7 and 5 where it has values between 1.84 and 2.6 (sandy silt and silty sand).

The correction of CPTm allows to obtain Ic lower than 2.6.

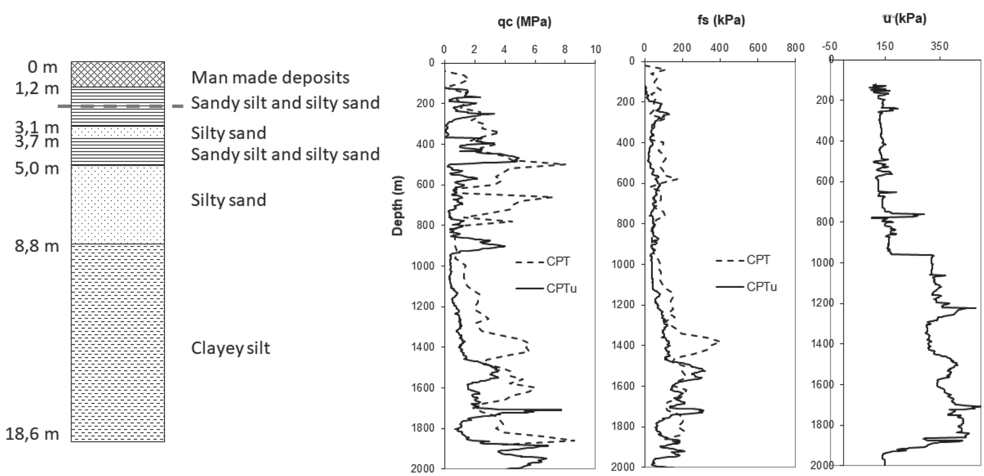

Figure 4. Case history 2. Simplified borehole, CPTm and CPTu qc, fs and u. In blue the Ground Water Table.

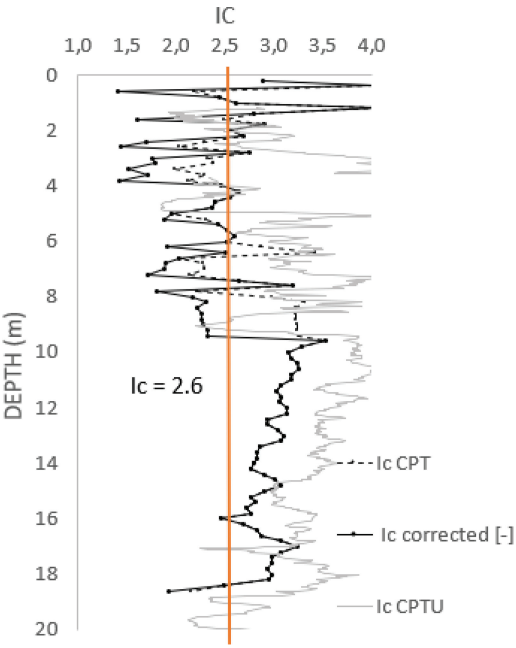

Figure 5. Case history 2. Ic variation with depth.

Also in this case the CPTu test identify thinner liquefiable horizons between 3.7 and 5 m (sandy silt). The Ic values calculated through CPTm indicate that for mechanical penetrometric test the liquefiable horizon is thicker and includes also sandy silt and silty sand.

The application of the correction for CPTm bring to an underestimation of Ic, with value less than 2.6 also for clay and silty soils.

4 CONCLUSIONS

A procedure developed by Meisina et al.2017 for correcting mechanical CPTm parameters (sleeve friction and Ic) was applied to a certain number of mechanical CPTm in the Emilia Romagna area interested by the seismic sequence of May 2012. Liquefiable horizons are composed by sand containing a certain amount of silt.

Results, in the case history documented in this study, demonstrated that:

1. All the tests detect liquefiable horizons (layers having Ic < 2.6 were assumed to be potentially liquefiable) but with different thickness, generally CPTu can misleading the interpretation of transitional soils as silty sand.
2. The correction of CPTm could in some cases underestimated the Ic and this lead to consider potentially liquefiable also clay and silty soils.
3. The Ic 2.6 threshold separating liquefiable and non liquefiable soils requires more analysis in the study area.

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