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Correction of Mechanical CPT Data for Liquefaction Resistance Evaluation

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Abstract - For more than 30 years, there has been considerable interest in using CPT also to evaluate the liquefaction resistance of soils. Unfortunately, most of the simplified methods used for liquefaction resistance evaluation only require in situ measurements from electrical cone penetrometers even if they are frequently applied using measurements from mechanical CPTs that are still preferred by current engineering practice in many countries. Erroneous estimates of liquefaction resistance and relevant non-conservative results are obtained by applying electrical CPT-based methods to mechanical CPT data without any form of correction. This study focuses on the developing of an appropriate procedure for correcting mechanical CPT data and provides modified equations for liquefaction resistance estimation by means of electrical CPT-based simplified methods. A dataset of more than 3900 pairs of measurements of cone tip resistance and sleeve friction were obtained from 44 sites selected in Northern and Central Italy and processed by means of statistical analyses. Suitable adjustments to CPT mechanical data were proposed for determining corrected liquefaction potential.

Keywords**:** Liquefaction; penetrometers; in situ testing, CPT, liquefaction potential

1. Introduction

Since 1932, cone penetration testing systems have developed into different equipment and interpretation criteria. Two major types of cone penetrometers may be identified: mechanical and electrical cone penetrometers. More advanced apparatus has been developed over time within this latter group for specific applications (piezocone, seismic cone and environmental penetrometers).

The electric cone penetrometer represented a significant improvement over the mechanical system with greater accuracy, repeatability and reliability of local measurements and, therefore, its use is rapidly growing and spreading. Nevertheless, in several countries, including Italy, the mechanical cone penetrometer is still used in engineering practice and the geotechnical databases provided by regional and national public institutions still mainly contain results from mechanical CPT tests.

For more than 30 years, there has been considerable interest in using CPT to evaluate the liquefaction resistance of soils and several simplified methods have been based on CPT results following both deterministic and probabilistic approaches (e.g., among the most recent, [1], [2], [3] and [4]). It cannot be excluded that some early work on liquefaction is based on data collected using a mechanical cone ([5]). However, the most recently compiled and widely used CPT-based methods mainly refer to data obtained from electrical cone penetrometers or piezocones following the International Reference Test and ASTM procedure ([6]).

Electrical CPT-based methods applied to mechanical CPT data without any form of correction lead to erroneous estimates of liquefaction resistance and relevant non-conservative results ([5]). In fact, the sleeve friction, f_s, is affected by the greatest error when the mechanical penetrometer is used ([7], [8]). At the same time, it has the greatest influence on the fine content and plasticity index assessment and, consequently, on soil classification and liquefaction susceptibility estimation.

This study aims at developing an appropriate procedure for correcting mechanical CPT data and providing modified equations for liquefaction resistance estimation by means of electrical CPT-based simplified methods. For this purpose, forty-four pairs of neighbouring electrical (CPTe) and mechanical (CPTm) tests were financed by the Regional Governments of Emilia-Romagna and Tuscany and performed in Northern and Central Italy and a dataset of more than

3900 pairs of measurements of cone tip resistance and sleeve friction pertaining to the same soil layers was appropriately selected.

2. Mechanical and Electrical CPT Data Comparisons

The two CPT tests of each pair were generally located within a distance ranging between 1 and 3 m. The minimum distance was chosen to avoid the natural soil disturbance induced by the tests; the maximum distance was selected to minimize as far as possible the influence of the horizontal inherent soil variability.

The first step in processing CPT measurements for implementing the dataset for statistical analyses consisted of correctly coupling cone tip resistance, q_c, and sleeve friction, f_s, from both mechanical and electrical tests for each explored soil layer. A depth correction of CPTm measurements was needed since mechanical cone penetrometers are not equipped with an inclinometer, and measurements may not correspond to the actual depth. Moreover, a moving average filter, with a span of 20 cm, was applied to CPTe readings that were later resampled at the same corrected depth of CPTm measurements, since CPTm and CPTe measurements generally refer to a volume of soil with different thickness (20 cm in CPTm; 1 or 2 cm in CPTe). When significant differences between the coupled mechanical and electrical q_c values were encountered, they were excluded by regressing raw data and diagnosing residuals to find the outliers that may be due to the inherent horizontal soil variability.

Finally, 3915 pairs of mechanical and electrical measurements of q_c and f_s were selected. The correlation matrix between electrical and mechanical parameters (q_c, f_s and the friction ratio, $R_f=f_s/q_c \cdot 100$) is shown in Table 1. The histograms and the empirical cumulative distribution functions (CDF) of the electrical-to-mechanical ratios (CPTe/CPTm) and their main statistics are shown in Figure 1 and Table 2, respectively. They suggest that mechanical data may significantly differ from electrical data in terms of sleeve friction, f_s, and derived parameters on which it has great influence (e.g R_f). On the contrary, a strong positive relationship (with a coefficient of correlation close to one) can be found between mechanical and electrical data if reference is made to the cone tip resistance, q_c.. It can also be observed that q_c exhibits quite more bell-shaped and symmetric (normal) distributions than f_s and R_f.

3. Proposed Correction Equations in Using Mechanical CPT Data for Liquefaction Evaluation

Simplified CPT-based methods share the same approach based on the comparison, at each depth, of liquefaction soil resistance and earthquake induced stresses, both normalised to the effective vertical overburden pressure. The earthquake-induced term, CSR, is generally estimated by means of the simplified procedure proposed by Seed and Idriss ([9]), unless the results from specific site response analyses are not available, and it depends mainly on the peak ground acceleration induced on the ground surface, PGA, and the moment magnitude of the earthquake, M_w.

On the other hand, different semi-empirical relationships have been developed by many Authors to evaluate the liquefaction resistance ratio with reference to earthquakes of moment magnitude $M_w=7.5$ ($CRR_{7.5}$) and an appropriate magnitude scaling factor ($MSF=CRR/CRR_{7.5}$) that is a function of the expected earthquake magnitude. These relationships generally provide the liquefaction resistance ratio in terms of equivalent clean sand cone tip resistance, q_{c1Ncs}, and are continuously updated as the worldwide liquefaction case history database increases. Among the most recently adopted CPT-based procedures, those proposed by Boulanger and Idriss ([2]) and Juang et al. ([3]), hereinafter mentioned as “B&I” and “J&al” respectively, were selected as the most representative and reliable for liquefaction hazard evaluation especially if the most recently observed liquefaction case histories of Christchurch (New Zealand) and Emilia-Romagna (Italy) are included ([10]). While the soil classification criteria adopted is generally the same originally proposed by Robertson ([11]) and the normalisation procedure applied to q_c is quite similar, the greatest difference among most of the CPT-based methods rely on the fine content evaluation and the correction applied to define the equivalent clean sand cone resistance, q_{c1Ncs}, as shown in Figure 2, where q_{c1Ncs} are calculated from the 3915 pairs of CPTe measurements by applying both the considered procedures and compared. The correction proposed by Boulanger and Idriss ([2]) furnishes much higher values of q_{c1Ncs} as the fine content increases (and the cone tip resistance decreases).

The equivalent clean sand cone penetration resistance, q_{c1Ncs}, was then selected for correction of mechanical CPT data as it is the parameter directly involved in evaluating liquefaction resistance, $CRR_{7.5}$, in almost all the simplified methods. Since q_{c1Ncs} is strongly dependent on the relationships used, significantly different results can be obtained. Further correction was determined for -soil behaviour type index, I_c, that is used for soil classification and, more specifically, to identify liquefiable or non-liquefiable soils (a threshold value $I_{c,lim}=2.6$ is currently assumed according to [12]).

1st and 2nd grade polynomial and power laws were tested to fit mechanical to electrical data. Results of regression analyses are shown in Figures 3a and 4a with reference to the equivalent clean sand cone resistance, q_{c1Ncs}, following the procedure proposed by [2] (B&I) and [3] (J&al), respectively. Further comparisons between corrected mechanical (estimated) values and electrical (target) values are shown in Figures 3b and 4b, for "B&I" and "J&al" approach respectively, where it is evident how the estimate errors are independent from the regressed variable, q_{c1Ncs}.

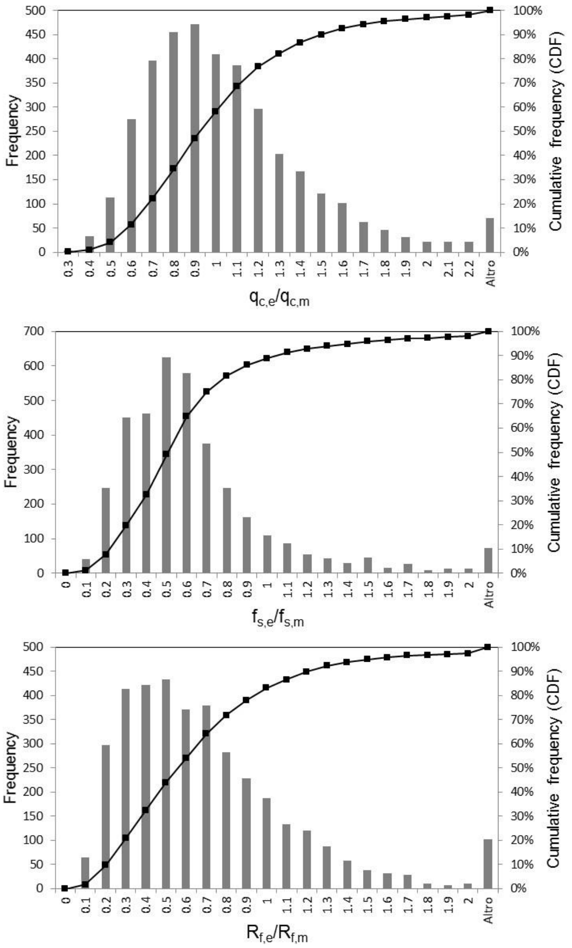

Fig. 1: Histograms and empirical cumulative distribution functions (CDF) of CPT_e/CPT_m ratios.

Table 1: Correlation matrix between mechanical (CPTm) and electrical (CPTe) data.

		Mechanical CPT data (CPTm)			Electrical CPT data (CPTe)		
		$q_{c,m}$	$f_{s,m}$	$R_{f,m}$	$q_{c,e}$	$f_{s,e}$	$R_{f,e}$
CPTm	$q_{c,m}$	1					
	$f_{s,m}$	0.53	1				
	$R_{f,m}$	0.52	0.06	1			
CPTe	$q_{c,e}$	0.96	0.49	-0.52	1		
	$f_{s,e}$	0.49	0.58	-0.08	0.43	1	
	$R_{f,e}$	0.44	0.01	0.50	0.53	0.32	1

Table 2: Main statistics of ratios between electrical and mechanical data (CPTe/CPTm).

	$q_{c,e}/q_{c,m}$	$f_{s,e}/f_{s,m}$	$R_{f,e}/R_{f,m}$
Mean	1.01	0.62	0.69
Standard deviation	0.45	0.72	0.89
Median	0.93	0.51	0.56
10th percentile	0.59	0.22	0.20
90th percentile	1.50	1.03	1.21
Skewness	2.75	22.46	25.98

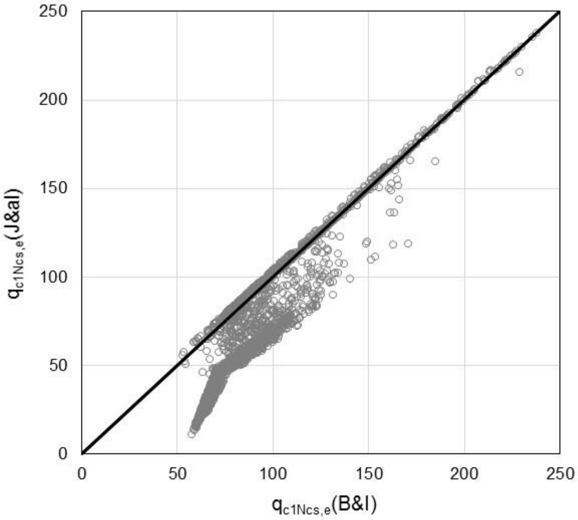

Fig. 2: q_{c1Ncs} values calculated from CPTe measurements by following the procedure proposed by [2] (B&I) and [3] (J&al).

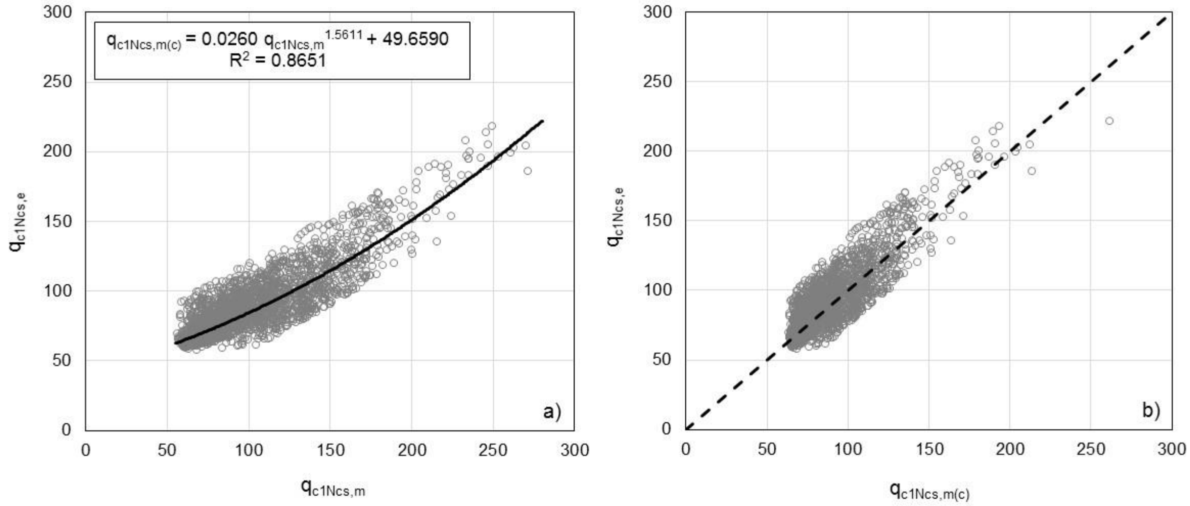

Fig. 3: Mechanical, uncorrected (a) and corrected (b), versus electrical q_{c1ncs} values following “B&I” procedure.

Results of regression analyses and comparisons between mechanical (corrected) and electrical values with reference to the soil behaviour type index, I_c, are shown in Figure 5.

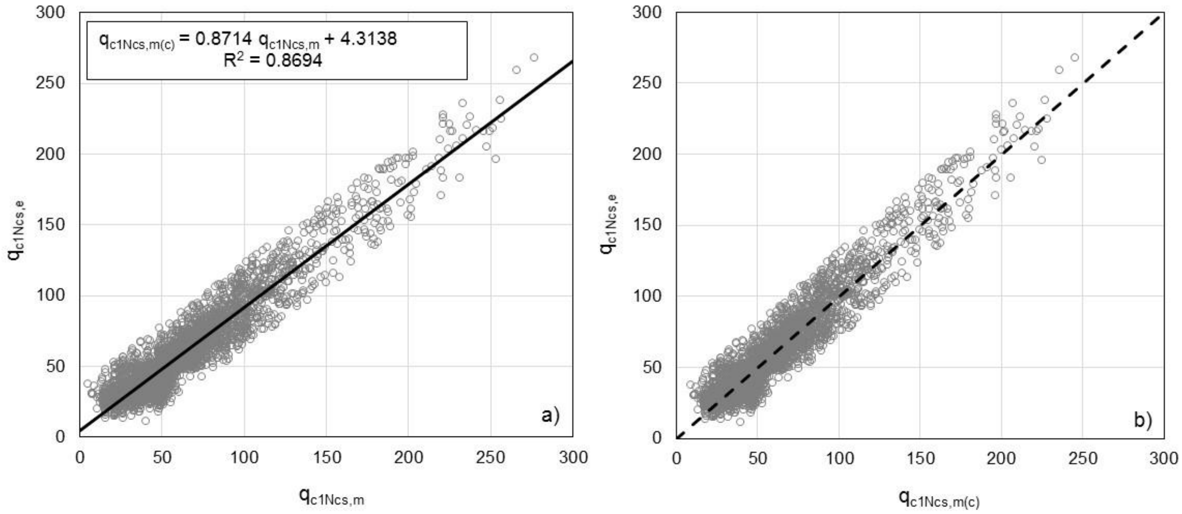

Fig. 4: Mechanical, uncorrected (a) and corrected (b), versus electrical q_{c1ncs} values following “J&al” procedure.

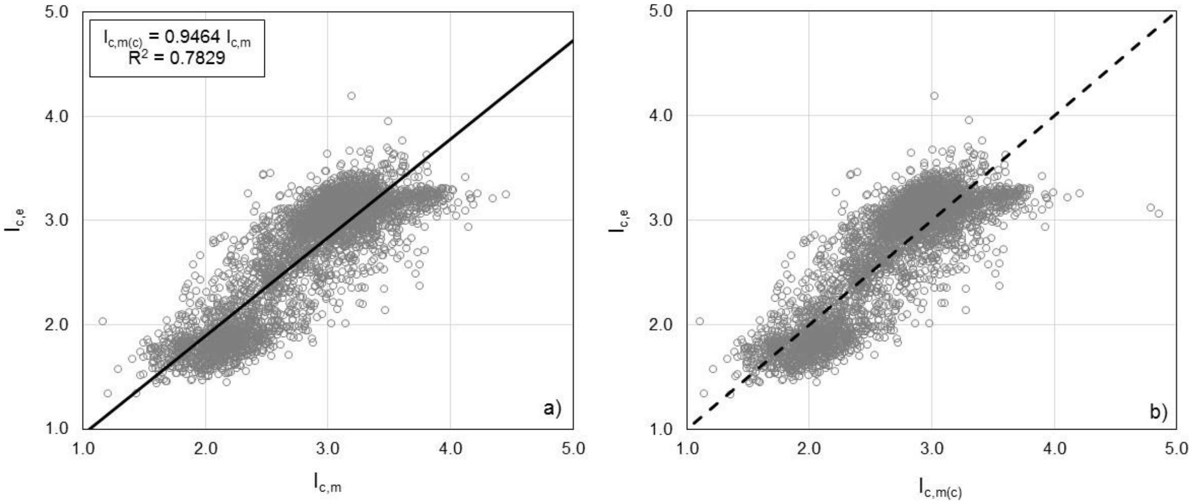

Fig. 5: Mechanical, uncorrected (a) and corrected (b), versus electrical I_c values.

The equations proposed for correcting mechanical q_{c1Ncs} and I_c values in adopting electrical CPT-based approaches are as follows:

$$q_{c1Ncs,m(c)} = \mu[q_{c1Ncs}] \pm \sigma[q_{c1Ncs}] = 0.0260\ q_{c1Ncs,m}^{1.5611} + 49.6590 \pm 10.00\ ; \qquad R^2 = 0.8651 \tag{1}$$
$$q_{c1Ncs,m(c)} = \mu[q_{c1Ncs}] \pm \sigma[q_{c1Ncs}] = 0.8714\ q_{c1Ncs,m} + 4.3138 \pm 10.80; \qquad R^2 = 0.8964 \tag{2}$$
$$I_{c,m(c)} = \mu[I_c] \pm \sigma[I_c] = 0.9464\ I_{c,m} \pm 0.28; \qquad R^2 = 0.7829 \tag{3}$$

Where R^2 is the coefficient of determination. Equations 1 and 2 refer to the approach proposed by Boulanger and Idriss ([2]) and by Juang et al. ([3]), respectively.

Histograms of residual errors of q_{c1Ncs} and I_c estimate are also reported in Figures 6 and 7, respectively, with their main statistics listed in Table 3. The residual distributions of q_{c1Ncs} are symmetric and bell-shaped and they can be approximately represented by normal distributions with mean, $\mu[q_{c1Ncs}] \cong 0$ and standard deviation, $\sigma[q_{c1Ncs}] \cong 10$.

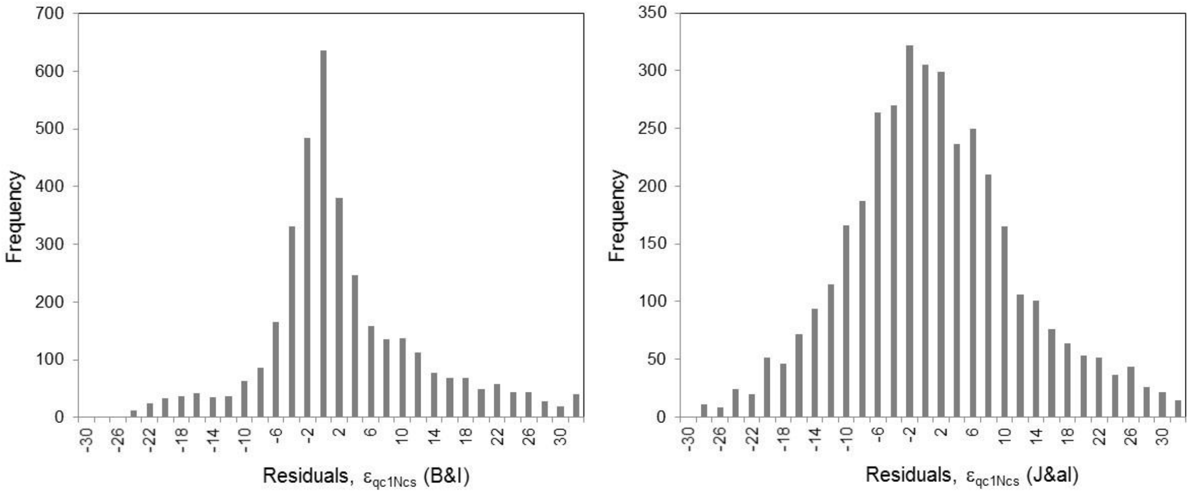

Fig. 6: Histogram of residual errors, ε, from q_{c1ncs} estimate by means of Eq. 1 (B&I) and 2 (J&al).

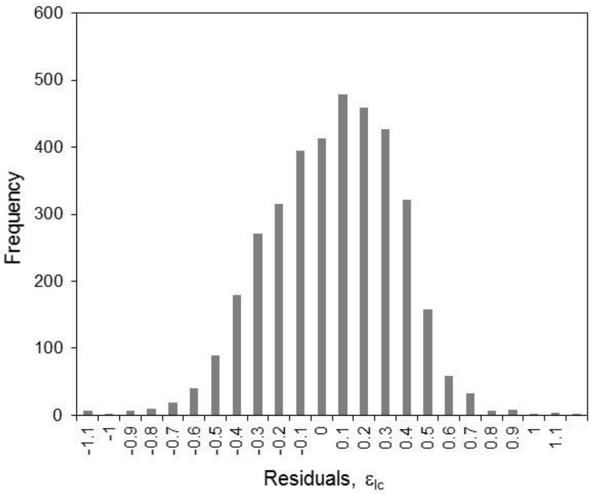

Fig. 7: Histogram of residual errors, ε, from I_c estimate by means of Eq. 3.

Table 3: Main statistics of residual errors, ε, from q_{c1Ncs} and I_c estimate (Eqs. (1)-(3)).

	q_{c1Ncs}		I_c
	B&I	J&al.	
Mean	1.36	-0.0025	0.0008
Standard deviation	10.03	10.80	0.31
Median	-0.53	-0.75	0.025
10th percentile	-8.12	-13.29	-0.39
90th percentile	15.59	14.34	0.36
Skewness	0.64	0.28	-0.48

4. Effects of Corrections on Liquefaction Potential Index (LPI) Evaluation

The liquefaction potential index (LPI) proposed by Iwasaki ([13]) was adopted both to quantify the effects of using mechanical CPT results instead of electrical CPTs when liquefaction simplified methods are applied and to test the reliability of the proposed correction procedure.

LPI is a cumulative index, ranging from 0 to 100, which is obtained by summing the appropriately weighted liquefaction potential of each layer of a vertical soil profile within a critical depth, z_{cr} (15 ÷ 20 m):

$$\mathrm{LPI} = \int_0^{z_{crit}} F(z)\cdot W(z)\cdot dz \tag{4}$$

Where $W(z)=200\cdot(1-z/z_{cr})/z_{cr}$ is a weighting function that gives increasing influence to layers at decreasing depths and F(z) is the liquefaction potential function (ranging from 0 to 1). F(z) is proportional to the safety factor against liquefaction, FSL=CRR/CSR. F(z) calculation is limited to layers susceptible to liquefaction, that is layers lying under the water table depth ($z > z_w$), with a certain lithological composition ($I_c < I_{c,lim}$) and mechanical resistance ($q_{c1Ncs} < 160$).

Firstly, LPI was determined on both the mechanical (LPI_m) and the electrical (LPI_e) CPT profiles collected from all the selected sites using both the procedures suggested by Boulanger and Idriss ([2]) and Juang et al. ([3]). Three reference earthquakes of different severity (named SS1, SS2 and SS3) characterised by different moment magnitude, M_w, and peak ground acceleration on the ground surface, PGA (SS1: M_w=6; PGA=0.15g; SS2: M_w=6.5; PGA=0.30g; SS3: M_w=7; PGA=0.45g) were considered. The same water level depth (z_w=1m) was assumed for all forty-four pair of CPTs and a cut-off value I_{clim}=2.6 was used to detect soils susceptible to liquefaction according to [12].

Secondly, corrected LPI values ($LPI_{m(c)}$) were evaluated by applying to mechanical q_{c1Ncs} values the corrections proposed by means of Eq. (1) and (2) (if the “B&I” or the “J&al“ method is considered, respectively) and by adopting a corrected cut-off value of I_c, as obtained from Eq. 3.

LPI_e values are plotted against LPI_m (empty symbols) or $LPI_{m(c)}$ (solid symbols) values on Figure 8 for all the considered reference earthquakes (SS1, SS2 and SS3) and following the procedures suggested by Boulanger and Idriss ([2]) and Juang et al. ([3]). Some considerations must be made: (1) empty symbols fall mainly below the line Y=X with increasing distances as the earthquake severity increases, it follows that electrical LPI values are almost always greater than mechanical values, so the use of mechanical CPT data to evaluate the liquefaction potential can lead to very non-conservative results especially if the “B&I” method is applied and high severity earthquakes occur (e.g. SS3) ; (2) solid symbols lie across the Y=X line with an increasing dispersion as the earthquake severity decreases (e.g. SS1) for both methods. It follows that suggested corrections for mechanical CPT data provide better estimates of LPI especially for the largest values.

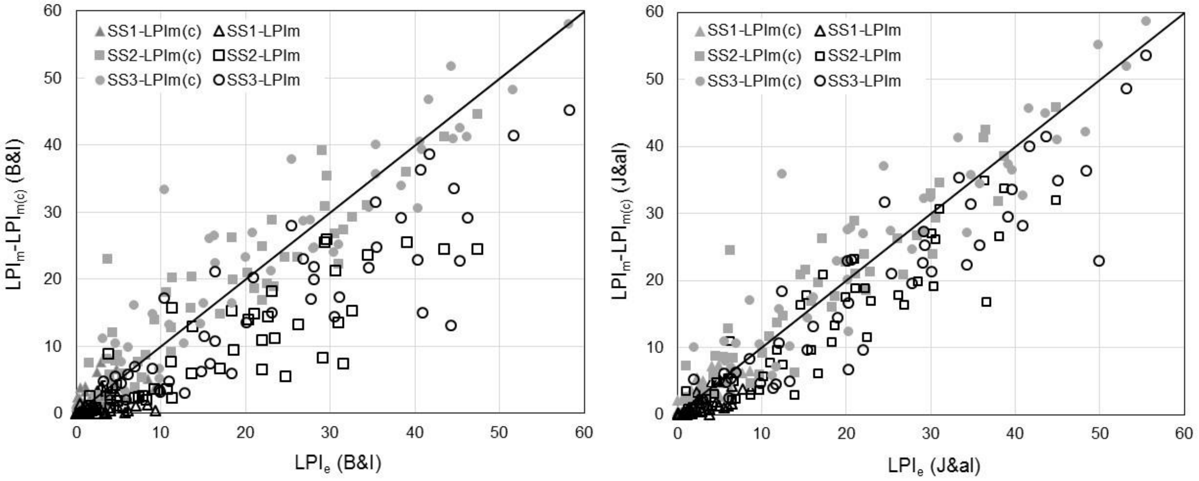

Fig. 8: LPI values from CPTe (LPI_e) and CPTm data assessed by means of “B&I” and “J&al” procedures for different seismic scenarios (SS1, SS2, SS3). Solid symbols refer to CPTm corrected data ($LPI_{m(c)}$), empty symbols refer to CPTm uncorrected data (LPI_m).

5. Conclusions

This study aims to develop an appropriate procedure for correcting mechanical CPT parameters and for providing modified equations for liquefaction resistance estimation by means of electrical CPT-based simplified methods. For this purpose, forty-four pairs of neighbouring electrical (CPTe) and mechanical (CPTm) tests were performed in Northern and Central Italy and a set of more than 3900 pairs of measurements of cone tip resistance and sleeve friction pertaining to the same soil layers was appropriately prepared. The results of the statistical analyses carried out suggest that mechanical data may significantly differ from electrical data in terms of sleeve friction, f_s, and derived parameters on which it has great influence (e.g R_f). On the contrary, a strong positive relationship can be found between mechanical and electrical data if reference is made to the cone tip resistance, q_c. The equivalent clean sand cone penetration resistance, q_{c1Ncs} and the soil behaviour type index, I_c were selected for correction of mechanical CPT data. Polynomial and power laws were tested to fit mechanical to electrical data with good correlation ($R^2 \geq 0.8$). The residual distributions of q_{c1Ncs} resulted symmetric and bell-shaped and they can be approximately represented by normal distributions with mean, $\mu[q_{c1Ncs}]\cong0$ and standard deviation, $\sigma[q_{c1Ncs}]\cong10$. The effects of the correction proposed were tested on the liquefaction potential evaluation, LPI calculated by applying to each pair of CPTm and CPTe profile the simplified procedures proposed by Boulanger and Idriss ([2]) and Juang et al. ([3]) and by considering three different seismic scenarios. It resulted that the electrical LPI values are systematically greater than mechanical values, so the use of mechanical CPT data to evaluate the liquefaction potential can lead to very non-conservative results especially if the Boulanger and Idriss method is applied and high severity earthquakes occur, and the suggested corrections for mechanical CPT data provide better estimates of LPI especially for the largest values.

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