The paper was published in the proceedings of the 7th International Conference on Earthquake Geotechnical Engineering and was edited by Francesco Silvestri, Nicola Moraci and Susanna Antonielli. The conference was held in Rome, Italy, 17 – 20 June 2019.

Earthquake Geotechnical Engineering for Protection and Development of Environment and Constructions – Silvestri & Moraci (Eds)

Liquefaction potential evaluation of intermediate soils from mechanical and electrical CPT's. The case study of Barberino di Mugello (Italy)

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ABSTRACT: Different CPT-based methods generally provide considerably different liquefaction potential values if they are applied to these soil mixtures of sandy silts to clayey sands and they often fail if the fine content and its plasticity are not known. Moreover, in several countries including Italy, most of the CPTs available for large scale studies (e.g. seismic microzonation) are mechanical; thus, the sleeve friction, especially if the fine content is high, can be affected by errors and lead to erroneous soil classification. Therefore, the simplified methods, which are based on electrical CPT measurements, can lead to erroneous estimates of liquefaction resistance and to considerably non-conservative results, if they are applied to mechanical CPT data without any form of correction. The present paper aims to compare three different CPT-based simplified methods for assessing the liquefaction potential of intermediate soil deposits in the municipality of Barberino di Mugello (Italy).

1 INTRODUCTION

Soils with intermediate grain-size distribution between clean sands and clays can be subject to extensive liquefaction phenomena as it was observed after the Emilia-Romagna earthquake of 2012 (Amorosi et al. 2016, Facciorusso et al. 2015a, b, Romeo et al. 2015, Vannucchi et al. 2012)

Alternations of saturated sandy silts, silts, silty and clayey sands may be encountered in a variety of depositional environments and within the first 10-15 m of depth. CPT-based simplified methods used for liquefaction resistance evaluation generally provide considerably different results in terms of liquefaction potential if they are applied to these soil mixtures and they often fail if the fine content and its plasticity are not known. Differences among these methods mostly rely on the adjustment factor for the equivalent clean sand cone tip resistance that is based on empirical estimation of the soil fine content and varies significantly method by method (Amoroso et al. 2017).

Furthermore, the CPT-based simplified methods require in situ measurements from electrical cone penetrometers even if they are frequently applied using mechanical CPTs that are still preferred by current engineering practice in many countries. It is well known that the sleeve friction, f_s, has the greatest influence on the fine content and the plasticity index assessment and, consequently, on soil classification and liquefaction susceptibility estimation. Furthermore, f_s is affected by the greatest error when a mechanical penetrometer is used. For these reasons, electrical CPT-based methods applied to mechanical CPT data without any form of correction lead to erroneous estimates of liquefaction resistance and significantly non-conservative results, especially if intermediate soils are considered. A procedure for correcting mechanical CPT data and providing modified equations and curves for liquefaction resistance estimation by means of CPT-based simplified methods was proposed first by Facciorusso et al. (2017).

Within a more wide project of seismic microzoning, several liquefaction risk analyses were performed extensively in five municipalities of the Mugello area in Northern Tuscany (Barberino di Mugello, Borgo San Lorenzo, San Piero a Sieve, Scarperia, Vicchio). Liquefaction potential was evaluated in more than 200 sites by applying three different CPT-based simplified methods, namely Boulanger and Idriss (2014), Juang et al. (2006) and Robertson (2009) (hereinafter 'B&I', 'J&al' and 'Rob', respectively) and, if mechanical CPT's were used, the abovementioned correction equations were applied. The case study of Barberino di Mugello was selected as representative of the geo-morphological and stratigraphic features of whole area under study and the results obtained as well as the effect of the correction are described and commented in the following.

2 DATASET AND INPUT PARAMETERS USED FOR THE ANALYSES

The Mugello region is a high seismicity area of Central Italy that includes the Appennine intramontane basin of the Sieve River where surface alluvial soil layers overlay fluvio-lacustrine soil deposits. Barberino di Mugello is the most important municipality of the studied area for population density, economic activities and extension.

Being the most numerous and reliable test for liquefaction potential evaluation, cone penetration tests were selected for liquefaction analyses within a larger dataset composed of more than 1441 in situ tests. The available dataset, as well as many databases provided by regional and national public institutions, contain mainly results from mechanical CPT tests.

Given that the recent soil deposits of the Sieve river basin are the most susceptible to liquefaction in the tested area (Figure 1), and the maximum critical depth for liquefaction ranges from 10 to 20 m, 209 mechanical CPT's (CPTm) and 16 electrical CPT's (CPTe) of length greater than 8 m and mostly located in the river basin were finally selected for the analyses in the whole studied area (Figure 1).

The CPT dataset falling within the municipality of Barberino di Mugello is composed of 18 CPTm's and 10 CPTE's and they will be discussed and commented below.

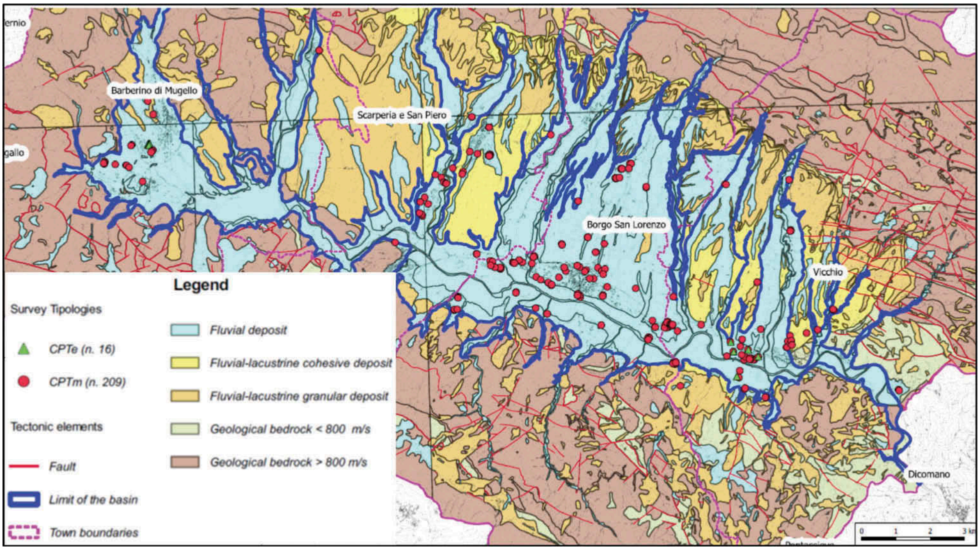

Figure 1. Geologic map of the area under study and location of the CPT's selected for liquefaction analyses (circles).

For each tested site, soil classification was inferred from CPTe and CPTm measurements by using the soil behavior type index, I_c, proposed by Robertson (1990) (Figure 2a) and the Schmertmann's soil classification chart (1978) (Figure 2b), respectively.

As it can be noted in Figure 2, silt and sand mixtures (i.e. alternations of sandy and clayey silts, silts and silty and clayey sands) are mostly encountered below 6 m of depth from the ground surface up to depths greater than 15 m. Accordingly, the critical depth, z_{cr}, for liquefaction potential evaluation was set at 20 m from the ground level.

According to the soil classification proposed by Robertson (1990), the I_c value that separates granular soils from cohesive soils is generally assumed by most simplified CPT-based methods as cut-off value of the soil behavior type index $I_{c,lim}$ for detecting soils susceptible to liquefaction. Given the high uncertainty in detecting subsoil stratigraphy by using CPT's, some Authors proposed different cut off values of I_c (e.g. Boulanger and Idriss 2014, Cubrinovski et al 2018).

The influence of the cut-off value adopted for LPI evaluation by means of the three simplified methods selected was evaluated by considering three cut-off values of the soil behavior type index $I_{c,lim}$ = 2.5, 2.6, 2.7. As clearly shown in Figure 2, the soil behavior type index I_c, mostly lie around the cut-off value $I_{c,lim}$ = 2.6 and it is expected that significantly higher liquefaction potential values could be obtained by increasing $I_{c,lim}$ from 2.6 to 2.7, as better evidenced in Figure 3. However, those higher calculated LPI values could result too conservative if the fine portion of soil had high plasticity index.

Thus, if simplified CPT-based methods are used for liquefaction potential evaluation of intermediate soils, direct measurements of the fine content and the plasticity index of those layers that could be susceptible to liquefaction should be collected or performed to eventually include or exclude those layers from calculations and, thus, to correct the liquefaction potential obtained by adopting the cut-off value that is generally assumed by most procedures ($I_{c,lim}$ = 2.6).

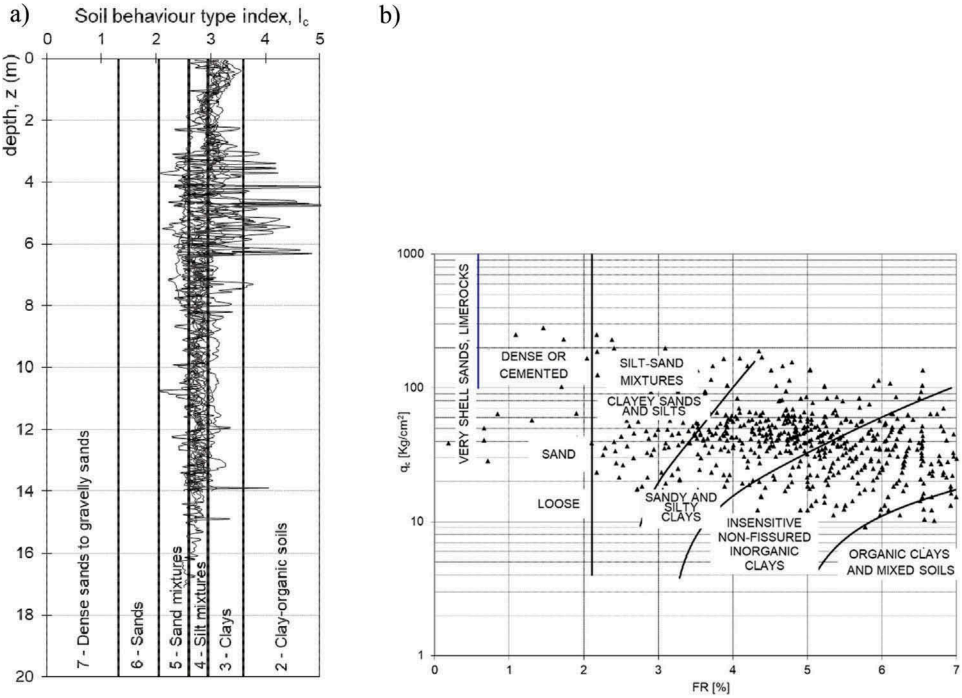

Figure 2. Soil behaviour type index, I_c vs depth for electrical CPT's (a) and Schmertmann's soil classification chart for mechanical CPT's (b). Note that I_c is calculated with reference to the Boulanger and Idriss (2014) method, but the same results can be obtained by using other methods.

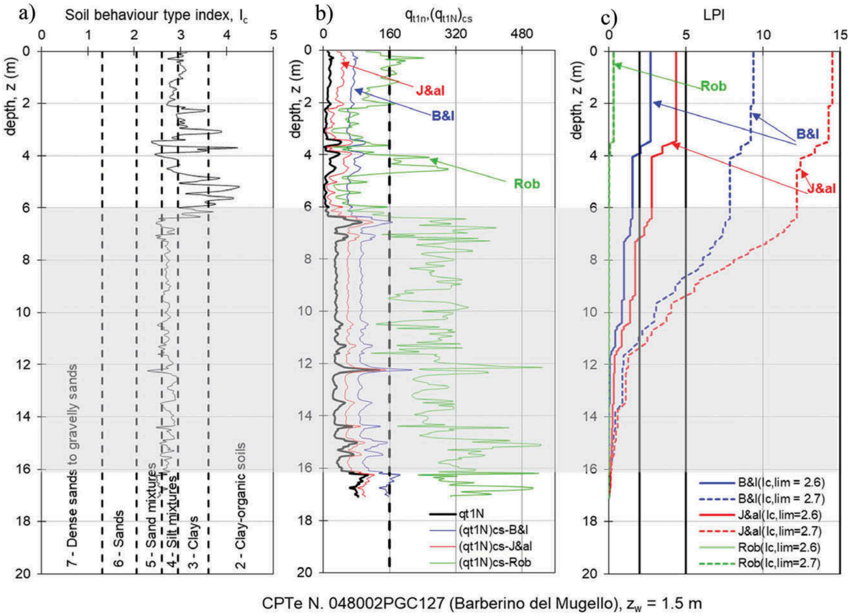

Figure 3. Soil behavior type index, I_c (a), normalized cone tip resistance, q_{c1N}, and equivalent clean sand cone tip resistance $(q_{c1N})_{cs}$ (b) and liquefaction potential index, LPI (c), vs depth obtained from CPTe measurements by B&I, J&al and Rob methods. LPI was evaluated by considering both $I_{c,lim}$ = 2.6 and $I_{c,lim}$ = 2.7.

In the following, results of LPI calculations for the whole dataset are shown and commented with reference to the same cut off value ($I_{c,lim}$ = 2.6) that is commonly assumed by most methods. to better evidence the differences among the simplified procedure considered and the influence of the correction proposed for two of them.

The depth of water table, z_w, was obtained from the available maps of the freatimetric levels and the most critical condition corresponding to the lowest depth of the groundwater was assumed at each site. Given the proximity of most of the CPT's to the Sieve river, the water table resulted for those sites mostly close to the ground surface.

The maximum expected moment magnitude assumed for the analyses with a return period of 475 years (M_w = 6.60) was deduced from the seismogenetic zonation ZS9 (Meletti &Valensise 2004). The maximum peak acceleration, a_{max}, expected on the ground surface for the same return period was calculated by following the procedure suggested by the Italian Seismic Buiding Code (Ministry of Infrastructure 2018). Given the mainly flat morphology of the tested area, the topographic effects were neglected in estimating the amplification effects (S_T=1), whereas the litostratigraphic effects were quantified through the amplification factor S_S that was empirically estimated by assuming a subsoil category C for each selected site. The resulting value of a_{max} obtained for the municipality of Barberino di Mugello by multiplying the reference acceleration expected on rock or rigid soil, a_g = 0.195g, by the litostratigraphic amplification factor, S_S=1.42, is 0.277g.

3 LIQUEFACTION POTENTIAL EVALUATION: RESULTS AND COMPARISONS

The simplified procedures proposed by Boulanger and Idriss (2014), Juang et al. (2006) and Robertson (2009) were applied to CPT measurements. They will be mentioned in the following as B&I, J&al and Rob procedures, respectively. Corrections for cyclic resistance ratio (CRR) were limited to the effects of the magnitude and the confining pressure by means of the magnitude scaling factor, MSF, and the correction factor, K_σ, respectively. To detect layers susceptible to liquefaction, only saturated layers lying below the water table within the critical depth z_{cr} and having a soil behavior type index $I_c < I_{c,lim}$ (=2.6) and an equivalent clean sand cone tip resistance $(q_{c1N})_{cs}<160$ were considered. For liquefaction potential evaluation, a limit value of 1.2 was adopted for the safety factor and the formulation expressed by Sonmez (2003) was adopted for the evaluation of the liquefaction potential index, LPI.

The results from the liquefaction analyses performed in the Barberino di Mugello municipality are plotted and compared in terms of LPI and hazard classes for each method considered in Figure 4.

Rob procedure systematically gives LPI values lower that those provided by the other methods, and it often detects absence of liquefaction where other methods estimate that liquefaction can potentially occur. However, Rob and B&I methods generally provide LPI values that both fall within the same hazard class, whereas the J&al procedure gives systematically higher LPI values that correspond to higher hazard classes (e.g. the average, the maximum and the minimum of the differences between the LPI values obtained from the J&al and the B&I procedures are 2.2, 5.7 and 0.6, respectively). These differences can be addressed principally to the correction factor proposed for the estimation of the equivalent clean sand cone tip resistance that is generally based on the empirical assessment of the soil fine content and, thus, it can provide significantly different values of LPI among the CPT-base simplified procedures, especially for intermediate soils (shaded area of Figure 3). As an example, the normalized con tip resistance, q_{c1N}, obtained from one of the available electrical CPT's, is plotted against depth in Figure 3 with the equivalent clean sand cone tip resistance obtained from the three methods. If the limit value of $(q_{c1N})_{cs}$ for liquefaction susceptibility is considered (dashed line of Figure 3), the differences among the LPI values estimated can be fully explained.

Following the procedure suggested by Facciorusso et al. (2017), correction equations were implemented to J&al and B&I procedures to take into account the error in using mechanical instead of electrical CPT measurements and they are listed below:

$$(q_{c1N})_{cs,EL} = 0.0260 \cdot (q_{c1N})_{cs,MEC}{}^{1.5611} + 49.6590 \quad (B\&I) \tag{1}$$

$$(q_{c1N})_{cs,EL} = 0.8714 \cdot (q_{c1N})_{cs,MEC} + 4.3138 \quad (J\&al) \tag{2}$$

$$I_{c,EL} = 0.9464 \cdot I_{c,MEC} \tag{3}$$

where $(q_{c1N})_{cs,MEC}$ and $(q_{c1N})_{cs,EL}$ are the equivalent clean sand cone tip resistance obtained from mechanical CPT (uncorrected) and from electrical CPT (corrected), respectively, $I_{c,MEC}$ and $I_{c,EL}$ are the soil behavior type index obtained from mechanical CPT (uncorrected) and from electrical CPT (corrected), respectively.

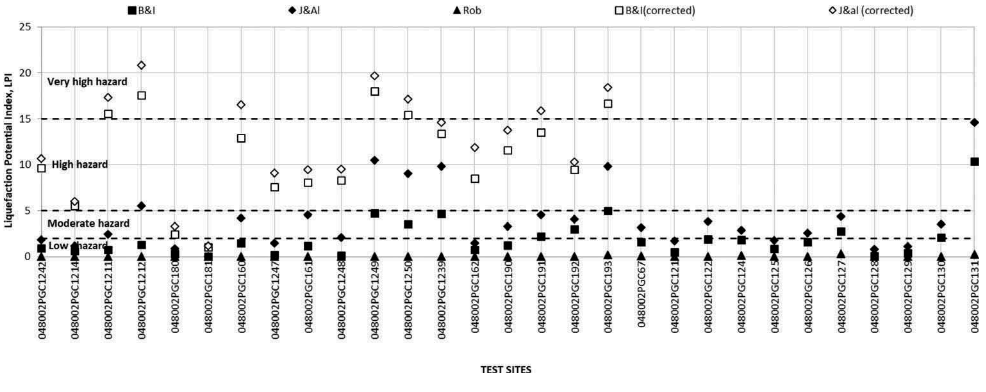

Figure 4. Uncorrected and corrected LPI values obtained at each investigated site in "Barberino di Mugello" municipality.

Thus, the liquefaction potential index LPI was recalculated for all the mechanical CPT's available and the corrected LPI values were compared with the uncorrected values in Figure 4. A further comparison is given by Figure 5, where corrected LPI values are plotted against the uncorrected values for both J&al and B&I methods.

If mechanical CPT's are considered, the influence of correction is significant and provide much higher LPI values. If the correction is applied, the liquefaction hazard evaluated at most

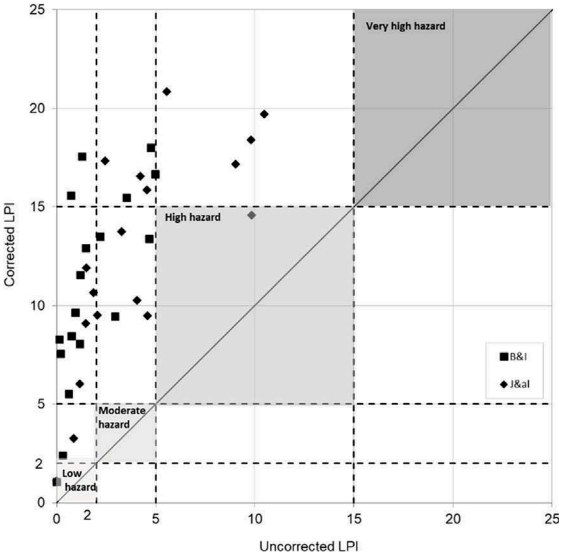

Figure 5. Corrected vs uncorrected LPI values provided by the B&I and J&al procedures for each investigated site in Barberino di Mugello municipality.

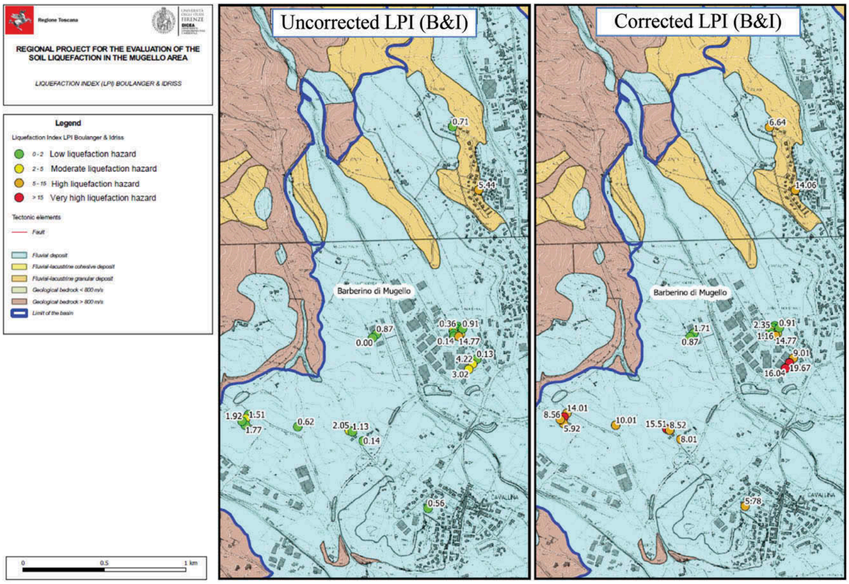

Figure 6. Maps of liquefaction hazard provided for a test area in Barberino di Mugello by using the Boulanger and Idriss (2014) method and implementing the correction procedure proposed by Facciorusso et al. (2017).

of the investigated sites, change from low to high or very high for both methods. The differences between uncorrected and corrected values are similar for both the B&I and J&al methods for most of the sites considered: the average, the maximum and the minimum of the differences between corrected and uncorrected LPI values are, respectively, 9.9, 17.1 and 0.1 for the B&I procedure and, respectively, 10.7, 19, -0.7 for the J&al method.

Based on the LPI values obtained for each tested sites, liquefaction hazard maps were finally drawn up. In Figure 6, as an example, liquefaction hazard maps are provided for an area of interest located in the municipality of Barberino di Mugello with reference both to uncorrected and corrected LPI values obtained from the B&I procedure.

4 CONCLUSIONS

Several liquefaction risk analyses were performed extensively in some municipalities of the Mugello area in Northern Tuscany falling within the Appennine intramontane basin of the Sieve river where surface alluvial soil layers overlay fluvio-lacustrine soil deposits. Attention was focused on the layers of intermediate soil, namely sandy silts, silts, silty and clayey sands, that are frequently encountered within the first 10-15 m and that cab be susceptible to liquefaction. The case study of Barberino di Mugello, the most important municipality for population density, economic activities and extension, was selected as representative of the geomorphological and stratigraphic features of whole area under study and, thus, presented and commented in the paper. The simplified CPT-based procedures proposed by Boulanger and Idriss (2014), Juang et al. (2006) and Robertson (2009) were selected for this study and they all gave different results in terms of LPI. These differences can be addressed principally to the correction factor proposed for the estimation of the equivalent clean sand cone tip resistance that is generally based on the empirical estimation of the soil fine content. This factor can vary significantly among the different CPT-based procedures used, especially if intermediate soils are considered. The procedure suggested by Robertson (2009) provided the highest correction factor values and, thus, the highest equivalent clean sand cone tip resistances for the intermediate soil layers. Thus, the lowest liquefaction potential were obtained by the Robertson procedure or, in some cases, absence of liquefaction where the two other methods estimate that liquefaction can potentially occur.

If intermediate soils are considered, great differences can be also noticed by selecting for the same procedure different cut-off values of the soil behavior type index. For the studied area, an increase of the cut-off value from the value 2.6, which is generally assumed by most methods, to 2.7 can determine a significant increase in the liquefaction potential index. Thus, if simplified CPT-based methods are used for liquefaction potential evaluation of intermediate soils, calculations should be performed by adopting different cut off values of I_c and comparing the obtained LPI values. If large differences are detected, direct measurements of the fine content and the plasticity index of those layers that could be susceptible to liquefaction should be collected or performed to correct the liquefaction potential obtained by adopting the cut-off value that is generally adopted by most methods ($I_{c,lim} = 2.6$). For microzonation studies, further investigations should be requested and, eventually, different methods for liquefaction evaluation should be suggested.

Since the dataset available for liquefaction analyses contain mainly results from mechanical CPT tests, the correction procedure proposed by Facciorusso et al. (2017) was implemented in Boulanger and Idriss (2014) and Juang et al. (2006) methods to take into account the error on the sleeve friction measurements. This issue has great influence on the fine content and plasticity index assessment and, consequently, on soil classification and liquefaction susceptibility, especially if intermediate soils are considered. In absence of correction, the LPI values estimated form mechanical CPT's resulted significantly lower than those obtained with correction, so leading to unconservative liquefaction hazard maps. Where only mechanical CPT's are not available, especially if intermediate soils susceptible to liquefaction are expected, electrical CPT's should be performed or correction procedure similar to that proposed should be applied.

ACKNOWLEDGEMENTS

This study was supported by Tuscany Regional Government and Fondazione Cassa di Risparmio di Firenze.

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