# DMT-based seismic liquefaction assessment accounting for the fines content effect: a case study in Emilia-Romagna, Italy

*Romualdo* Cecchi[1], *Anna* Chiaradonna[1#], and *Paola* Monaco[1]

[1]*University of L'Aquila, Dept. of Civil, Construction-Architectural and Environmental Engineering, L'Aquila, Italy*
[#]*Corresponding author: anna.chiaradonna1@univaq.it*

## ABSTRACT

Simplified methods for seismic liquefaction assessment based on the flat dilatometer test (DMT), in which the liquefaction triggering curve is defined based on the horizontal stress index ($K_D$), have been proposed over the years. One major drawback of the existing methods, valid for clean sand, is the lack of a correction factor for the fines content. An updating of the empirical relationship *CRR*-$K_D$ proposed by Chiaradonna and Monaco (2022) to incorporate the effects of the fines content is currently under development and validation. This paper illustrates the results obtained from application of the new method at the site of San Carlo – Terre del Reno (Ferrara) located in the Emilia-Romagna plain (Italy), where widespread liquefaction occurred in the 2012 seismic sequence. A comprehensive site characterization from previous in-situ and laboratory tests carried out by various research groups is available for the sand, silty sand and sandy silt deposits in the San Carlo area. The performance of the new *CRR*-$K_D$ curve accounting for the fines content effect is compared with that obtained by adopting the "clean sand" curves proposed by Chiaradonna and Monaco (2022), as well as with that obtained by using the CPT-based method by Boulanger and Idriss (2014). Even though verified only for specific Italian soils in this area and requiring further field validation, the proposed approach appears as promising to improve the DMT-based liquefaction assessment in silty sands.

**Keywords:** flat dilatometer test; soil liquefaction; semi-empirical liquefaction chart; fines content.

## 1. Introduction

Simplified methods based on in-situ test results are commonly used for assessment of earthquake-induced soil liquefaction, at least as a first step before performing more complex analyses. In general, the adopted approach lies within the framework of the "simplified procedure" based on the comparison, at any depth, of the seismic demand (cyclic stress ratio *CSR*) and the capacity of the soil to resist liquefaction (cyclic resistance ratio *CRR*). Liquefaction may occur when *CSR* is greater or equal than *CRR*. The *CSR* is evaluated based on the main characteristics of the assumed scenario earthquake. The *CRR* is commonly estimated by using semi-empirical charts based on the results of in-situ tests, such as the cone penetration test (CPT), the standard penetration test (SPT), shear wave velocity ($V_S$) measurements, and the flat dilatometer test (DMT). For each in-situ test method, *CRR* is obtained as a function of a normalized and corrected parameter assumed as representative of the soil liquefaction resistance.

In the widely used charts based on CPT, SPT and $V_S$, largely developed in the last decades, the *CRR* curves are defined as an empirical boundary separating datapoints related to liquefaction and no-liquefaction cases observed in real earthquakes. However, for the DMT-based methods the liquefaction case history database is still limited. In addition, one major drawback of the existing approach for DMT is related to the lack of a correction factor for the fines content in the assessment of the DMT-based cyclic strength of soils.

An updating of the DMT-based method proposed by Chiaradonna and Monaco (2022) to incorporate the effects of the fines content is currently under development and validation. Chiaradonna and Monaco (2024) presented one preliminary application of the new proposed approach to a case study involving a sketch of a river dyke in the Emilia-Romagna plain (Italy), highly damaged by the 2012 Emilia earthquake. This paper illustrates an additional evaluation of the performance of this new approach to another well-known case study in the same region, San Carlo – Terre del Reno (Ferrara), where widespread liquefaction occurred in the 2012 seismic sequence.

## 2. DMT-based liquefaction assessment: background and recent developments

### 2.1. Simplified DMT-based methods for clean sand

Simplified methods for estimating the *CRR* based on DMT test results have been proposed over the years. In these methods the liquefaction triggering curve is defined based on the horizontal stress index ($K_D$), a key parameter obtained from DMT interpretation. The $K_D$ parameter was originally defined by Marchetti (1980) based on the measured first DMT pressure ($p_0$) normalized to the effective overburden stress. Various studies (e.g., Monaco et al. 2005) have pointed out that $K_D$ reflects cumulatively various stress history effects, i.e., overconsolidation, in-situ stress state, prestraining/aging, and is correlated with the relative density and the in-situ state parameter. All these factors are known to greatly influence the cyclic strength of soils. Therefore $K_D$ has been recognized as a suitable index parameter of liquefaction resistance. Hence $K_D$ can be used in a similar way as the normalized and corrected parameters employed in methods based on other in-situ tests, e.g., the normalized corrected cone tip resistance $q_{c1N}$ for CPT, the normalized energy-corrected blow count $(N_1)_{60}$ for SPT, and the overburden stress corrected shear wave velocity $V_{S1}$.

Fig. 1 shows a summary of the most recent $CRR$-$K_D$ curves (for magnitude 7.5 earthquakes) proposed by Monaco et al. (2005), Tsai et al. (2009), Robertson (2012), Marchetti (2016), and Chiaradonna and Monaco (2022). The DMT $K_D$-based methods currently available are valid for clean sand and do not account for the effect of the fines content ($FC$).

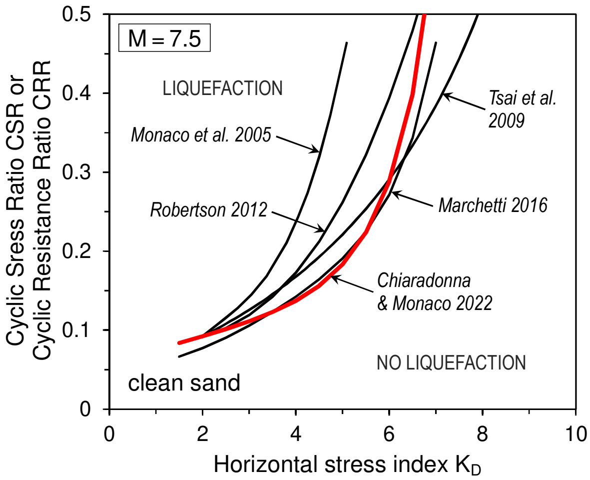


**Figure 1.** Summary of recent DMT-based $CRR$-$K_D$ correlations for clean sands

DMT-based methods have been applied to various case studies in Italy and around the world. The application of these methods at different sites in the Emilia-Romagna plain, in soil conditions similar to those found at the site considered for this study, is reported by Monaco et al. (2016), Porcino et al. (2019), Amoroso et al. (2022) and others. However, the field performance database for validation of the DMT-based methods is currently limited. This substantial drawback is partially mitigated by the fact that most DMT-based methods have been formulated by translation of existing liquefaction triggering curves developed for CPT (and SPT), which are instead supported by a vast field performance case history database (Monaco 2022).

In particular, the latest liquefaction triggering curve for DMT (red curve in Fig. 1) was developed by Chiaradonna and Monaco (2022) by adopting the CPT-based framework provided by Boulanger and Idriss (2014). The CPT curve was translated into an equivalent DMT curve using an average direct correlation between the corrected cone resistance $q_{c1Ncs}$ (equivalent corrected cone tip resistance for clean sand) and $K_D$ obtained from re-elaboration of different CPT-DMT data sets (Tsai et al. 2009, Tonni et al. 2015). Such direct correlation was found to be compatible with the approach previously described by Robertson (2012), also used by Marchetti (2016). However, like other existing DMT-based methods, also the method proposed by Chiaradonna and Monaco (2022) is valid for clean sand and its general application is limited by the lack of a correction factor for the fines content.

## 2.2. Generalization of DMT-based methods accounting for the *FC* correction

Chiaradonna and Monaco (2024) outlined a tentative approach for implementing the $FC$ correction in their previous $CRR$-$K_D$ curve developed for clean sand (Chiaradonna and Monaco 2022). The approach proposed for DMT is similar to the approach implemented by Boulanger and Idriss (2014) in CPT- and SPT-based methods, in which the $CRR$ is estimated as a function of a normalized soil resistance parameter including the effect of the fines content. The normalized values $q_{c1N}$ (CPT) and $(N_1)_{60}$ (SPT) are converted into equivalent clean sand values $q_{c1Ncs}$ and $(N_1)_{60cs}$, respectively, by introducing the corrections $\Delta q_{c1N}$ and $\Delta(N_1)_{60}$ depending on $FC$, having the form:

$$q_{c1Ncs} = q_{c1N} + \Delta q_{c1N} \quad (1)$$

$$(N_1)_{60cs} = (N_1)_{60} + \Delta (N_1)_{60} \quad (2)$$

Hence, both $q_{c1Ncs}$ and $(N_1)_{60cs}$ are obtained as the sum of two terms: the first one ($q_{c1N}$, $(N_1)_{60}$) is related to the normalization of the measured data to the effective overburden stress, the second one ($\Delta q_{c1N}$, $\Delta(N_1)_{60}$) accounts for the beneficial effect of the fines content, which is "fictitiously" translated into an increase of the soil resistance parameters ($q_{c1Ncs}$, $(N_1)_{60cs}$).

Similarly, in the approach proposed for DMT the horizontal stress index ($K_D$), which is already a normalized parameter and consequently maintains its original definition, is converted into an equivalent clean sand value ($K_{D,cs}$) by introducing the correction $\Delta K_D = f(FC)$, defined as follows:

$$K_{D,cs} = K_D + \Delta K_D \quad (3)$$

The expression proposed by Chiaradonna and Monaco (2024) for the correction $\Delta K_D$ retains a functional form similar to the $\Delta(N_1)_{60}$ correction formulated by Boulanger and Idriss (2014):

$$\Delta K_D = \exp\left( a + \frac{b}{FC + c} - \left( \frac{d}{FC + c} \right)^2 \right) \quad (4)$$

where $a$, $b$, $c$, $d$ are regression coefficients to be calibrated based on experimental data.

By adopting this approach, a generalized form of the $CRR$-$K_D$ curve by Chiaradonna and Monaco (2022), which accounts for the effect of the fines content and is applicable to all sands, is derived as follows:

$$CRR_{7.5} = \exp(0.001109 K_{D,cs}^4 - 0.00569 K_{D,cs}^3 + 0.000625 K_{D,cs}^2 + 0.221 K_{D,cs} - 2.8) \quad (5)$$

where $CRR_{7.5}$ is the $CRR$ for magnitude 7.5.

For the practical use of Eq. (5), the correction $\Delta K_D$ expressed by Eq. (4) as a function of *FC* needs to be determined. The $\Delta K_D$ values could be calculated based on *FC* data from laboratory grain size distribution analyses on samples retrieved from nearby boreholes, whenever available. However, in a routine site investigation this information is rarely available during the execution of the in-situ testing campaign. Therefore an estimation of the fines content based on the DMT results would be useful, at least for a preliminary evaluation.

For this purpose, the material index $I_D$ obtained by DMT interpretation, defined by Marchetti (1980) to identify soil type, appears as a suitable parameter. In fact, $I_D$ is a parameter that reflects the mechanical soil behaviour, not a soil classification index based on real grain size distribution, similarly to the Soil Behavior Type (SBT) Index $I_c$ obtained from CPT. A relationship between DMT-$I_D$ and CPT-$I_c$ was proposed by Robertson (2009), considering the similar intended use of these two parameters. According to this relationship, the value $I_c = 2.6$ generally assumed as an approximate boundary between sand-like and clay-like behaviour for CPT corresponds roughly to $I_D \approx 1$ for DMT. This $I_D$ value can be used in DMT-based liquefaction assessment as a threshold value to screen out clay-like soils (having $I_D < 1$), similar to $I_c > 2.6$ in CPT-based methods.

A correlation $FC - I_D$ was recently developed by Di Buccio et al. (2023) for Emilia alluvial plain soils, having the form:

$$FC = x_D(-31 I_D + 91) \quad (6)$$

where *FC* is expressed in percentage and $x_D$ is a coefficient ranging from 0.5 and 2.

### 2.3. Suggested procedure for calibration of the proposed *FC* correction

The proposed approach for incorporating the *FC* effect in DMT-based liquefaction assessment requires the determination of the regression coefficients *a*, *b*, *c*, *d* in Eq. (4). At present these coefficients have not yet been established in a form of general validity, which would require a robust calibration based on large and consistent experimental data sets from different sites. Therefore the current recommendation is to calibrate the proposed *FC* correction for each specific site, by combining relevant data from in-situ DMT tests and laboratory tests on samples taken from nearby boreholes. The following procedure is suggested:

1. in the laboratory, obtain *FC* from grain size distribution analyses and $CRR_{7.5}$ (*CRR* for magnitude 7.5, corresponding approximately to *CRR* at 15 cycles) from cyclic simple shear or other tests;
2. in situ, obtain $I_D$ and $K_D$ values from DMT at the same depths of the tested samples;
3. calibrate the $FC - I_D$ relationship by Di Buccio et al. (2023) (Eq. 6) based on the *FC* and $I_D$ data pairs;
4. calibrate the proposed $\Delta K_D - FC$ relationship (Eq. 4) as best-fit of the $CRR$-$K_{D,cs}$ correlation (Eq. 5) based on the same-depth laboratory *FC* and $CRR_{7.5}$ and $K_D$ data.

Chiaradonna and Monaco (2024) presented a preliminary application on the proposed approach at the Scortichino site, Emilia (Italy), where a canal dyke was highly damaged by the 2012 Emilia earthquake. For the silty sand / sandy silt deposits at this site an extensive soil characterization from in-situ and laboratory tests was available (Tonni et al. 2015). In this paper the proposed *FC* correction is calibrated for a different case study in the same region, as described in the following.

## 3. Calibration of the *FC* correction on a case study: San Carlo – Terre del Reno (Ferrara, Italy)

### 3.1. Site conditions and geotechnical data

The village of San Carlo, part of the municipality of Terre del Reno, Ferrara (Italy), was affected by widespread liquefaction in the May 20$^{th}$, 2012 Emilia earthquake, as documented by several studies (Vannucchi et al. 2012, Emergeo Working Group 2013, Fioravante et al. 2013, Facciorusso et al. 2014, 2015, Lai et al. 2015, Papathanassiou et al. 2015, among others).

The village of San Carlo was constructed above the abandoned channel of the Reno river. The ancient river banks can still be recognized as the areas morphologically more elevated (about 5-6 m) than the surrounding floodplain. Due to the past river digressions, the sediments in the area are characterized by a complex succession of alluvial deposits belonging to different depositional environments. These deposits consist mostly of sands, silty sands and sandy silts.

In the aftermath of the 2012 Emilia earthquake, the area of San Carlo was extensively investigated by a large number of geotechnical and geophysical in-situ tests carried out by various working groups. The available experimental data set comprises several boreholes, piezocone (CPTU) and seismic piezocone (SCPTU) tests. Four seismic dilatometer tests (SDMT) were carried out in 2013 as part of the INGV-DPC – S2-2012 "COBaS" project (Romeo et al. 2015). Laboratory tests, including cyclic triaxial tests and resonant column tests, were carried out on undistubed samples taken from the boreholes.

### 3.2. Calibration of the *FC* – $I_D$ relationship

The $FC - I_D$ relationship by Di Buccio et al. (2023) (Eq. 6) was calibrated based on data pairs of *FC* determined in the laboratory on samples taken from boreholes close to the SDMT soundings and same-depth $I_D$ values from SDMT (dots in Fig. 2). For the site under study, the application of Eq. (6) provided a value of the coefficient $x_D = 1.06$. For comparison, Fig. 2 also includes one $FC - I_D$ data point obtained by Chiaradonna and Monaco (2024) using the same approach at the Scortichino site (Tonni et al. 2015), leading in that case to $x_D = 0.7$.

Fig. 3 shows the comparison of the depth profiles of *FC* estimated from $I_D$ obtained from two representative SDMT soundings (SDMT3, SDMT4) using Eq. (6) with $x_D = 1.06$, and the laboratory *FC* values determined on samples taken from nearby boreholes.

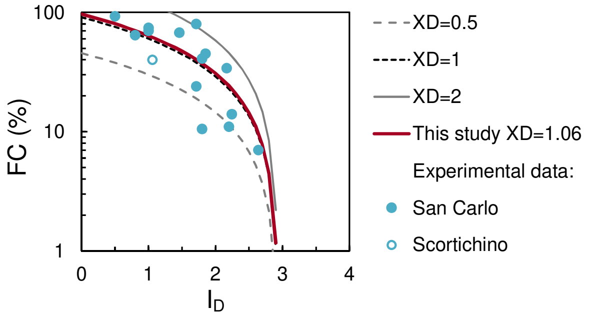


**Figure 2.** Calibration of the $FC-I_D$ relationship by Di Buccio et al. (2023) for the case study of San Carlo.

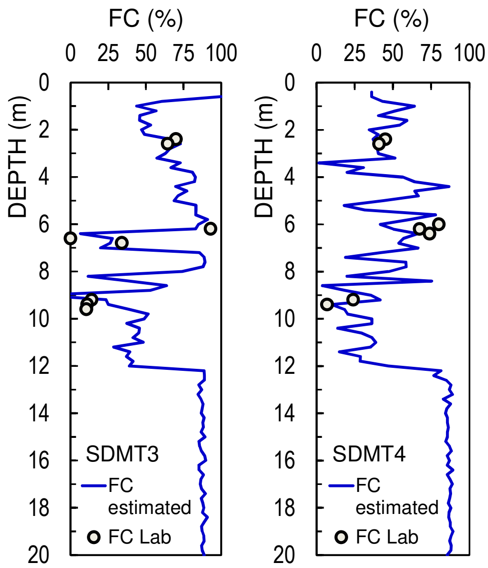


**Figure 3.** Comparison of $FC$ estimated from $I_D$ according to Di Buccio et al. (2023) and $FC$ from laboratory tests.

## 3.3. Calibration of the $\Delta K_D-FC$ relationship

The proposed $\Delta K_D-FC$ relationship, described by Eq. (4), was calibrated for this specific site by assuming as a reference the results of cyclic triaxial tests performed on undisturbed silty sand samples taken from boreholes close to the SDMT soundings. For each tested sample, by coupling the $CRR$ obtained at 15 cycles (corresponding approximately to $CRR_{7.5}$) and the same-depth $K_D$ from SDMT, the related $K_{D,cs}$ was back-calculated by inverting the relationship in Eq. (5). Then $\Delta K_D$ was derived from Eq. (3) and associated to the $FC$ for calibration of the $a$, $b$, $c$, $d$ coefficients in Eq. (4). The value of $FC$ corresponding to $\Delta K_D$ was obtained using the relationship by Di Buccio et al. (2023), assuming an average value of $I_D$ for the two SDMT soundings under consideration (SDMT3, SDMT4). The $K_D$ value associated to $\Delta K_D$ corresponds to the average value of the $K_D$ profiles of the two soundings. The data used for the calibration are reported in Table 1.

The resulting $\Delta K_D-FC$ relationship, shown in Fig. 4, is the following:

$$\Delta K_D = \exp\left(1.04 + \frac{5.75}{FC-5.56} - \left(\frac{11.2}{FC-5.56}\right)^2\right) \qquad (7)$$

Fig. 4 shows that Eq. (7), calibrated based on the San Carlo data, approximates reasonably well also one $\Delta K_D-FC$ data point obtained by Chiaradonna and Monaco (2024) at the Scortichino site.

**Table 1.** Data used for the calibration of Eq. (4)

| Depth (m) | $CRR$ (15 cycles) | $FC$ (%) | $K_D$ | $K_{D,cs}$ | $\Delta K_D$ |
|---|---|---|---|---|---|
| 2.20 | 0.239 | 39.7 | 2.94 | 5.64 | 2.71 |
| 2.40 | 0.247 | 54.9 | 2.90 | 5.70 | 2.80 |
| 6.30 | 0.240 | 46.6 | 2.29 | 5.65 | 3.36 |
| 9.25 | 0.229 | 33.4 | 2.26 | 5.55 | 3.29 |
| 9.40 | 0.274 | 24.4 | 3.00 | 5.90 | 2.90 |

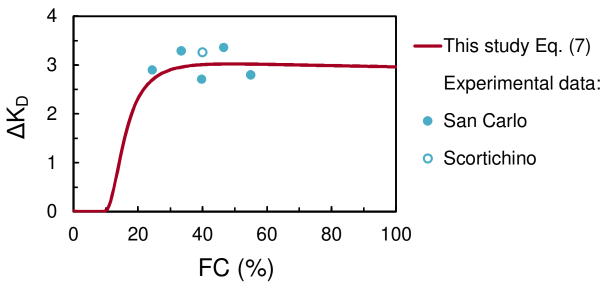


**Figure 4.** Calibration of the $\Delta K_D-FC$ relationship for the case study of San Carlo.

## 3.4. Effect of the *FC* correction on DMT-based liquefaction assessment

In order to evaluate the effect of the proposed $FC$ correction, liquefaction analyses were carried out by using DMT-based methods developed for clean sands, which do not account for the fines content, and by the proposed approach, which includes the $FC$ correction.

The analyses were carried out assuming as seismic input is the May 20$^{th}$, 2012 Emilia mainshock. The related earthquake parameters required for evaluating the cyclic stress ratio ($CSR$) were assumed based on the study by Minarelli et al. (2022). For the considered mainshock this study reports a moment magnitude $M_w = 6.1$ and an estimated maximum acceleration in the San Carlo area $a_{max} = 0.46$ g. In the DMT-based methods, $CSR$ at each depth and the magnitude scaling factor ($MSF$) were calculated according to Idriss and Boulanger (2008). The groundwater table was assumed at a depth of 4.60 m, as observed during the site investigation.

Fig. 5 compares the results obtained by adopting the proposed approach taking into account the fines content effect (Eq. 5) and by using the method by Chiaradonna and Monaco (2022) without the $FC$ correction. The results refer to one representative SDMT sounding (SDMT4). The depth profile of $FC$ shown in Fig. 5 was estimated through Eq. (6) with $x_D = 1.06$ (Fig. 2). The $K_{D,cs}$ profile, superimposed to the $K_D$ profile, was obtained by applying the Eq. (3) using $\Delta K_D$ from Eq. (7) (Fig. 4).

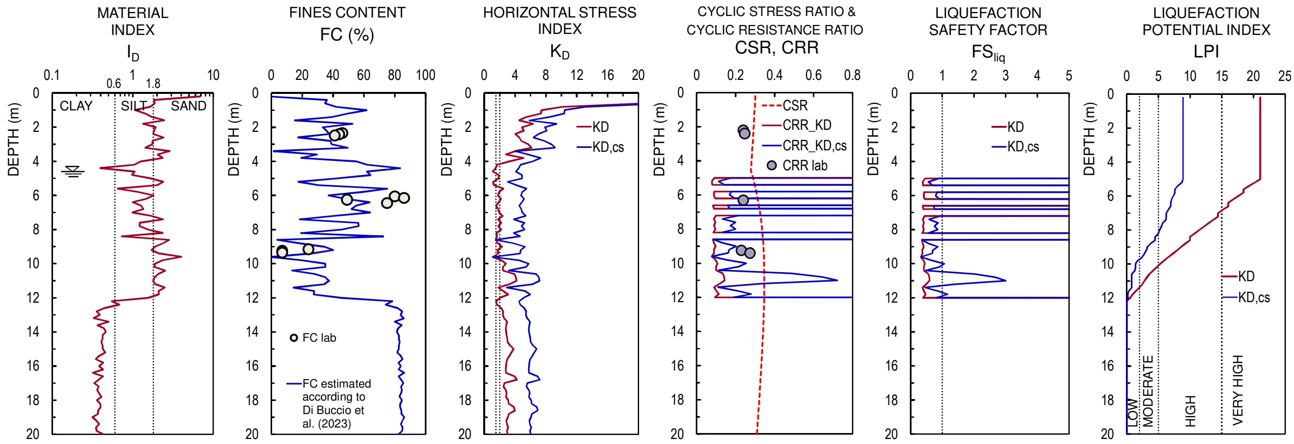


**Figure 5.** Comparison of results of DMT-based liquefaction analyses using the method by Chiaradonna and Monaco (2022) without the *FC* correction (red lines) and the proposed approach including the *FC* correction (blue lines).

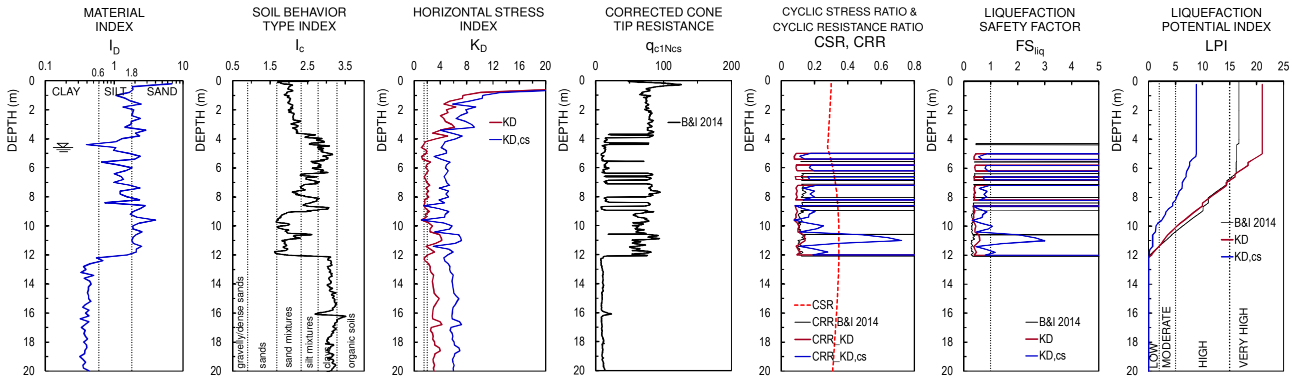


**Figure 6.** Comparison of results of liquefaction analyses based on DMT using the method by Chiaradonna and Monaco (2022) without (red lines) and with (blue lines) the *FC* correction, and based on CPT using the method by Boulanger and Idriss (2014).

As expected, the *CRR* estimated by Eq. (5) is generally higher than the *CRR* obtained without the *FC* correction, leading to a higher safety factor against liquefaction ($FS_{liq}$). The "integral" liquefaction susceptibility at the test location was also evaluated using the liquefaction potential index *LPI* proposed by Iwasaki et al. (1984), according to the modified form proposed by Sonmez (2003). The comparison between the two *LPI* profiles in Fig. 5 highlights a substantial influence of the *FC* correction: *LPI* decreases from about 21 to about 9, and the related classification of the soil liquefaction potential moves from "very high" to "high", when the *FC* effect is taken into account.

On the other hand, the introduction of the *FC* correction does not affect the identification of the liquefiable layer, which is detected between about 5 m and 12 m depth in both cases. Incidentally, the use of the other $K_D$-based methods shown in Fig. 1 (Monaco et al. 2005, Tsai et al. 2009, Robertson 2012 and Marchetti 2016), which do not account for the *FC* effect, provided results very similar to those obtained using the method by Chiaradonna and Monaco (2022) without the *FC* correction.

In Fig. 6 the results of DMT-based liquefaction assessment carried out according to Chiaradonna and Monaco (2022), both without and with the proposed *FC* correction, are compared with those obtained using the CPT-based method by Boulanger and Idriss (2014). The input data were obtained from a seismic piezocone test (SCPTU2) carried out close to the SDMT sounding (SDMT4). Fig. 6 also shows the depth profiles of the "corresponding" parameters related to soil behaviour type for the two in-situ tests, i.e., $I_D$ for DMT and $I_c$ for CPT.

The comparison in Fig. 6 shows that the *LPI* obtained from CPT according to Boulanger and Idriss (2014) is about 17, an intermediate value between the *LPI* obtained from DMT without and with the *FC* correction (about 21 and 9, respectively). The two independent approaches identify substantially to the same liquefiable soil layer, except at depths between about 4.6 m and 6.5 m. In this depth interval it is possible that some soil layers may be screened out as "clay-like" based on CPT having $I_c > 2.6$, but not based on DMT having $I_D > 1$.

## 4. Conclusions

Simplified methods for seismic liquefaction assessment based on DMT, which make use of $K_D$ as an index parameter, may offer a useful addition to current popular methods based on CPT or SPT. This potential is in line with the general recommendation towards the use of "redundant" correlations based on different in-situ techniques / parameters in the "simplified procedure". In addition, the SDMT permits to obtain two parallel independent evaluations of the liquefaction potential, one based on $V_S$ and one on $K_D$.

The main drawbacks of the existing DMT-based methods are related to the lack of a correction factor for the fines content, and to the still limited experimental validation based on field performance data from real earthquakes.

Current research focuses on the implementation of the *FC* correction in DMT-based triggering curves. This paper illustrates the application of a new proposed approach to a case study in the Emilia-Romagna plain (Italy), where widespread liquefaction occurred in the 2012 earthquake. A preliminary application of the proposed approach to another case study in the same area was presented by Chiaradonna and Monaco (2024).

The proposed relationships for the implementation of the *FC* correction have been calibrated so far based only on specific Italian soil deposits affected by liquefaction in the 2012 Emilia earthquake. Future studies and further insights are needed to confirm or disclaim the obtained results in different soil conditions. Nevertheless, the proposed approach appears as promising to improve the DMT-based liquefaction assessment in silty sand / sandy silt deposits.

The implementation of an adequate case history database for validation of the DMT-based approach could support the introduction of more consistent liquefaction triggering curves, taking into account the fines content influence, also as an effort to address the challenging task of characterizing the liquefaction behaviour of intermediate soils.

## Acknowledgements

This study is supported by the Research Project of National Interest 'TRANSITION – characTeRization And modelling of iNtermediate Soils through Innovative approaches for robust design of straTegic Infrastructures and protection Of risk-seNsitive areas' funded by the Italian Ministry of University and Research (PRIN 2022 – Project 2022PZW7FL – Grant E53D23003630006) and by the Project DPC-ReLUIS 2022-2024 (WP16 – Task 1 'Site response analysis and liquefaction') funded by the Italian Civil Protection Department.

The SDMT tests at the San Carlo site were carried out as part of the Project INGV-DPC 2012-2013 – S2-2012 'COBaS: Constraining Observations into Seismic Hazard' (Task 8 'Liquefaction' coordinated by Prof. Roberto W. Romeo). Additional information and data from in-situ and laboratory tests at the site were shared within the scope of the same project.

The authors are grateful to Dr Luca Martelli and the Geological, Seismic and Soil Survey of the Emilia-Romagna Regional Authority (RER) for providing access to the RER soil investigation database.

## References

Amoroso, S., M. F. García Martínez, P. Monaco, L. Tonni, G. Gottardi, K. M. Rollins, L. Minarelli, D. Marchetti, and K. J. Wissmann. 2022. "Comparative Study of CPTU and SDMT in Liquefaction-Prone Silty Sands with Ground Improvement." J Geotech Geoenviron Eng 148, no. 6: 04022038, https://doi.org/10.1061/(ASCE)GT.1943-5606.0002801

Boulanger, R. W. and I. M. Idriss. 2014. "CPT and SPT liquefaction triggering procedures." Report No. UCD/GCM-14/01, University of California at Davis, USA.

Chiaradonna, A., and P. Monaco. 2022. "Assessment of liquefaction triggering by seismic dilatometer tests: comparison between semi-empirical approaches and non-linear dynamic analyses." In Proc. 20th Int. Conf. on Soil Mechanics and Geotechnical Engineering ICSMGE 2022, Sydney, Australia, M. Rahman and M. Jaksa (eds), 335–340, https://www.issmge.org/uploads/publications/1/120/ICSMGE_2022-58.pdf

Chiaradonna, A., and P. Monaco. 2024. "Estimation of the soil cyclic resistance by flat dilatometer accounting for the fines content effect." In Proc. 6th Int. Conf. on Earthquake Geotechnical Engineering 8ICEGE, Osaka, Japan.

Di Buccio, F., C. Comina, D. Fontana, L. Minarelli, F., Vagnon, and S. Amoroso. 2023. "Fines content determination through geotechnical and geophysical tests for liquefaction assessment in the Emilia alluvial plain (Ferrara, Italy)." Soil Dyn Earthq Eng 173: 108057, https://doi.org/10.1016/j.soildyn.2023.108057

Emergeo Working Group. 2013. "Liquefaction phenomena associated with the Emilia earthquake sequence of May–June 2012 (Northern Italy)." Nat Hazards Earth Syst Sci 13, no. 4: 935–947, https://doi.org/10.5194/nhess-13-935-2013

Facciorusso, J., C. Madiai, and G. Vannucchi. 2014. "Soil liquefaction analyses in a test-area affected by the 2012 Emilia-Romagna earthquake (Italy)." In Engineering Geology for Society and Territory – Vol. 5, G. Lollino et al. (eds), 1111–1114, https://doi.org/10.1007/978-3-319-09048-1_211

Facciorusso, J., C. Madiai, and G. Vannucchi. 2015. "CPT-based liquefaction case history from the 2012 Emilia earthquake in Italy." J Geotech Geoenviron Eng 141(12): 1032–1051, https://doi.org/10.1061/(ASCE)GT.1943-5606.0001349

Fioravante, V., D. Giretti, G. Abate, S. Aversa, D. Boldini, P. P. Capilleri, A. Cavallaro, D. Chamlagain, T. Crespellani, F. Dezi, J. Facciorusso, A. Ghinelli, S. Grasso, G. Lanzo, C. Madiai, M. R. Massimino, M. Maugeri, A. Pagliaroli, C. Rainieri, G. Tropeano, F. Santucci De Magistris, S. Sica, F. Silvestri, and G. Vannucchi. 2013. "Earthquake geotechnical engineering aspects of the 2012 Emilia-Romagna earthquake (Italy)." In Proc. 7th Int. Conf. on Case Histories in Geotechnical Engineering, Chicago, USA, Paper No. EQ-5.

Idriss, I. M., and R. W. Boulanger. 2008. "Soil liquefaction during earthquakes." EERI Publication No. MNO-12, Earthquake Engineering Research Institute, Oakland.

Iwasaki, T., T. Arakawa, and K. Tokida. 1984. "Simplified procedures for assessing soil liquefaction during earthquakes." Soil Dyn Earthq Eng 3, no. 1: 49–58, https://doi.org/10.1016/0261-7277(84)90027-5

Lai, C. G., F. Bozzoni, M.-D. Mangriotis, and M. Martinelli. 2015. "Soil Liquefaction during the 20 May 2012 M5.9 Emilia Earthquake, Northern Italy: Field Reconnaissance and Post-Event Assessment." Earthquake Spectra 31(4): 2351–2373, https://doi.org/10.1193/011313EQS002M

Marchetti, S. 1980. "In Situ Tests by Flat Dilatometer." J Geotech Eng Div 106, no. 3: 299–321.

Marchetti S. 2016. "Incorporating the stress history parameter $K_D$ of DMT into the liquefaction correlations in clean uncemented sands." J Geotech Geoenviron Eng 142, no. 2: 04015072, https://doi.org/10.1061/(ASCE)GT.1943-5606.0001380

Minarelli, L., S. Amoroso, R. Civico, P. M. De Martini, S. Lugli, L. Martelli, F. Molisso, K. M. Rollins, A. Salocchi, M. Stefani, G. Cultrera, G. Milana, and D. Fontana. 2022. "Liquefied sites of the 2012 Emilia earthquake: a comprehensive database of the geological and geotechnical features (Quaternary alluvial Po plain, Italy)." Bull Earthq

Eng 20: 3659–3697, https://doi.org/10.1007/s10518-022-01338-7

Monaco, P. 2022. "Combined use of CPT & DMT: Background, current trends and ongoing developments." In Cone Penetration Testing 2022, Proc. 5th Int. Symp. on Cone Penetration Testing CPT'22, Bologna, Italy, G. Gottardi and L. Tonni (eds), 94-106, https://doi.org/10.1201/9781003308829-7

Monaco, P., S. Marchetti, G. Totani, and M. Calabrese. 2005. "Sand liquefiability assessment by flat dilatometer test (DMT)." In Proc. 16th Int. Conf. on Soil Mechanics and Geotechnical Engineering, Osaka, Japan, 2693–2697, https://doi.org/10.3233/978-1-61499-656-9-2693

Monaco, P., L. Tonni, G. Gottardi, M. Marchi, L. Martelli, S. Amoroso, and L. Simeoni. 2016. "Combined use of SDMT-CPTU results for site characterization and liquefaction analysis of canal levees." In Proc. 5th Int. Conf. on Geotechnical and Geophysical Site Characterization ISC'5, Gold Coast, Australia, B. M. Lehane et al. (eds), 615–620, https://www.issmge.org/uploads/publications/25/26/ISC5_082.pdf

Papathanassiou, G., A. Mantovani, G. Tarabusi, D. Rapti, and R. Caputo. 2015. "Assessment of liquefaction potential for two liquefaction prone areas considering the May 20, 2012 Emilia (Italy) earthquake." Eng Geol 189: 1–16, https://doi.org/10.1016/j.enggeo.2015.02.002

Porcino, D. D., P. Monaco, and L. Tonni. 2019. "Evaluating Seismic Behavior of Intermediate Silty Sands of Low Plasticity from Emilia Romagna, Italy." Geotech Spec Publ 2019-March (GSP 308), Geo-Congress 2019: Earthquake Engineering and Soil Dynamics, Philadelphia, USA, 341–351, https://ascelibrary.org/doi/10.1061/9780784482100.035

Robertson, P. K. 2009. "CPT-DMT Correlations." J Geotech Geoenviron Eng 135, no. 11: 1762–1771, https://doi.org/10.1061/(ASCE)GT.1943-5606.0000119

Robertson, P. K. 2012. "The James K. Mitchell Lecture: Interpretation of in-situ tests – some insights." In Proc. 4th Int. Conf. on Geotechnical and Geophysical Site Characterization ISC'4, Porto de Galinhas, Brazil, R. Coutinho and P. W. Mayne (eds), 3–24.

Romeo, R. W., S. Amoroso, J. Facciorusso, L. Lenti, C. Madiai, S. Martino, P. Monaco, D. Rinaldis, and F. Totani. 2015. "Soil liquefaction during the Emilia, 2012 seismic sequence: investigation and analysis." In Engineering Geology for Society and Territory – Vol. 5, G. Lollino et al. (eds), 1107–1110, https://doi.org/10.1007/978-3-319-09048-1_210

Sonmez, H. 2003. "Modification of the liquefaction potential index and liquefaction susceptibility mapping for a liquefaction-prone area (Inegol, Turkey)." Environ Geol 44: 862–871, https://doi.org/10.1007/s00254-003-0831-0

Tonni, L., G. Gottardi, S. Amoroso, R. Bardotti, L. Bonzi, A. Chiaradonna, A. d'Onofrio, V. Fioravante, A. Ghinelli, D. Giretti, G. Lanzo, C. Madiai, M. Marchi, L. Martelli, P. Monaco, D. Porcino, R. Razzano, S. Rosselli, P. Severi, F. Silvestri, L. Simeoni, G. Vannucchi, and S. Aversa. 2015. "Interpreting the deformation phenomena triggered by the 2012 Emilia seismic sequence on the Canale Diversivo di Burana banks." Rivista Italiana di Geotecnica 49, no. 2: 28–58 (in Italian).

Tsai, P., D. Lee, G. T. Kung, and C. H. Juang. 2009. "Simplified DMT-based methods for evaluating liquefaction resistance of soils." *Eng Geol* 103, no. 1–2: 13–22, https://doi.org/10.1016/j.enggeo.2008.07.008

Vannucchi, G., T. Crespellani, J. Facciorusso, A. Ghinelli, C. Madiai, A. Puliti, and S. Renzi. 2012. "Soil liquefaction phenomena observed in recent seismic events in Emilia-Romagna Region (Italy)." Ingegneria sismica 29, no. 2–3: 20–30.