Estimation of the soil cyclic resistance by flat dilatometer accounting for the fines content effect

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ABSTRACT

The application of semi-empirical charts based on in-situ tests results represents the first step in the earthquake-induced soil liquefaction assessment. Among them, the CPT-based charts have been largely developed in the last decades, especially after the 2010-2011 Canterbury earthquakes in New Zealand, while the main drawback of the existing approach based on DMT is related to the lack of a correction factor for the fines content. In this regard, this study proposes a new empirical relationship between the Cyclic Resistance Ratio and the horizontal stress index where the effects of the fines content are incorporated. The new method is calibrated on a specific site located in the Emilia-Romagna plain (Italy), where an extensive soil characterization from in-situ and laboratory tests was available for the silty sand and sandy silt deposits affected by liquefaction after the 2012 Emilia earthquake. Even though verified only for Italian natural soils, the new approach allows to reduce substantially the discrepancy between the results obtained when the CPT-based and the DMT-based methods are applied.

Keywords: flat dilatometer test, soil liquefaction, semi-empirical liquefaction chart, fines content

1 INTRODUCTION

The first step in earthquake-induced soil liquefaction assessment is the application of semi-empirical charts based on in-situ tests, such as cone penetration test (CPT), standard penetration test (SPT), flat dilatometer test (DMT), shear wave velocity measurements (V_S). The use of the seismic version of the flat dilatometer (SDMT) or the seismic cone (SCPT) has the double advantage to allow the application of two charts by associating the mechanical parameter (horizontal stress index or cone tip resistance) to the V_S, for a more robust assessment of the soil liquefaction potential. However, while the CPT-based charts have been largely developed in the last decades, the main 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.

In this regard, this study proposes an updated liquefaction triggering curve for DMT, with the formulation of a new empirical relationship between the cyclic resistance ratio (*CRR*) and the horizontal stress index (K_D) where the effects of the fines content are incorporated. The new curve is calibrated on the collected data from several sites located in the Emilia-Romagna plain (Italy), where an extensive soil characterization from in-situ and laboratory tests is available for the silty sand and sandy silt deposits affected by liquefaction after the 2012 Emilia earthquake.

The performance of the new proposed curve is compared with that obtained by adopting the curve proposed by Chiaradonna and Monaco (2022) and that obtained using CPT results along a sketch of a river dyke highly damaged by the 2012 Emilia earthquake.

2 BACKGROUND

Simplified methods for estimating the cyclic resistance ratio (*CRR*) based on DMT test results have been proposed over the years, including the most recent by Monaco et al. (2005), Tsai et al. (2009), Robertson (2012), Marchetti (2016), Chiaradonna and Monaco (2022). DMT-based methods have been applied to various case studies in Italy and around the world (Monaco et al. 2011, 2016; Amoroso et al. 2014, 2015, 2017, 2018, 2020, 2022; Boncio et al. 2018; Porcino et al. 2019; Monaco and Amoroso 2019). By all methods, the liquefaction triggering curve is defined based on the horizontal stress index (K_D). This parameter, introduced by Marchetti (1980), has been recognized as a suitable parameter for liquefaction assessment due to its sensitivity to a number of factors (i.e., stress history, pre-straining/aging, in-situ stress state, relative density) which are known to influence liquefaction resistance (Monaco et al. 2005). The proposed CRR-K_D curves are valid for magnitude 7.5 earthquakes and clean uncemented sand.

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All the above-mentioned methods have in common a strong link with CPT-based methods in their origin, in an effort to relate in some way to the field performance database that provides a vast experimental validation for current methods based on CPT, but is currently limited for DMT-based methods (Monaco 2022).

The latest liquefaction triggering curve for DMT was proposed by Chiaradonna and Monaco (2022) adopting the CPT-based framework provided by Boulanger and Idriss (2014), in which the following terms are defined:

$$q_{c1Ncs} = q_{c1N} + \Delta q_{c1N} \tag{1}$$

$$q_{c1N} = C_N \cdot \frac{q_c}{P_a} \tag{2}$$

$$C_N = \left(\frac{P_a}{\sigma'_v}\right)^m \leq 1.7 \tag{3}$$

$$m = 1.338 - 0.249 \cdot q_{c1Ncs}^{\,0.264} \tag{4}$$

$$\Delta q_{c1N} = \left(11.9 + \frac{q_{c1N}}{14.6}\right) \exp\left(1.63 - \frac{9.7}{FC+2} - \left(\frac{15.7}{FC+2}\right)^2\right) \tag{5}$$

where q_{c1Ncs} = corrected cone resistance, q_c = measured cone resistance, P_a = atmospheric pressure, σ'_v = effective overburden stress and FC = fines content (i.e., percentage of soil having particles diameter smaller than 0.075 mm), taken into account by Δq_{c1N}. The value of q_{c1Ncs} must be found by trial and error.

The CPT-based empirical relationship proposed by Boulanger and Idriss (2014) is the following:

$$CRR_{M=7.5,\sigma'=1} = \exp\left(\frac{q_{c1Ncs}}{113} + \left(\frac{q_{c1Ncs}}{1000}\right)^2 - \left(\frac{q_{c1Ncs}}{140}\right)^3 + \left(\frac{q_{c1Ncs}}{137}\right)^4 - 2.8\right) \tag{6}$$

Eq. (6) provides the cyclic resistance ratio of the soil characterized by a given value of q_{c1Ncs} for a reference 7.5 magnitude earthquake and effective overburden stress equal to 1. Further corrections to Eq. (6) are necessary to take into account: (i) the overburden stress, via the correction factor K_σ, and (ii) the actual magnitude of the earthquake via the Magnitude Scaling Factor (*MSF*).

Chiaradonna and Monaco (2022), using the CPT-DMT data set by Tsai et al. (2009) for 5 different sites in Taiwan, and considering only CPT data providing a soil behavior type index I_c between 1.5 and 2.6, established a direct correlation between K_D and q_{c1Ncs} (Fig. 1). Despite the dispersion, the Taiwan data set is well described by a linear trend with a slope of 20. Fig. 1 also shows a second data set (Tonni et al. 2015) from the Scortichino site, Italy, where both CPT and SDMT data were available, considering only data for $FC < 10\%$. The Scortichino data set is better interpreted by a linear trend with a slope of about 30.

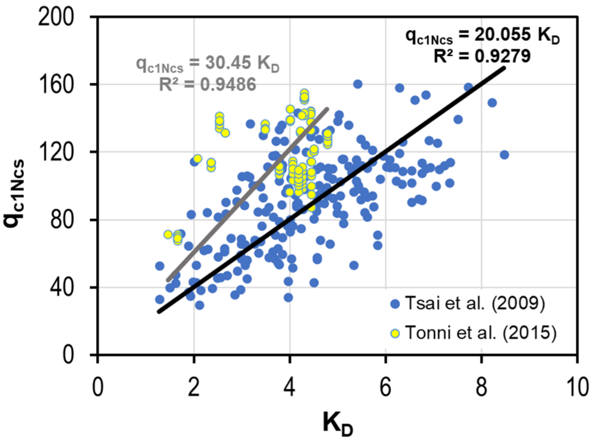

Fig. 1. Relationship between q_{c1Ncs} and K_D from published CPT-DMT data records at different sites (Chiaradonna and Monaco 2022).

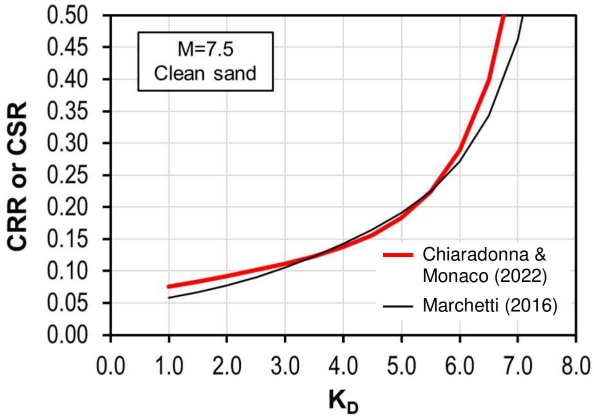

Fig. 2. Relationship *CRR*-K_D by Chiaradonna and Monaco (2022) compared with the previous curve proposed by Marchetti (2016).

Due to the discrepancy in the two considered data sets, also considering the limited amount of processed data, Chiaradonna and Monaco (2022) adopted an average coefficient of 25:

$$q_{c1Ncs} = 25K_D \tag{7}$$

which is compatible with the approach described by Robertson (2012), also used by Marchetti (2016). By substituting the Eq. (7) into the Eq. (6) proposed by Boulanger and Idriss (2014), Chiaradonna and Monaco obtained a new *CRR*-K_D curve (Fig. 2):

$$CRR = \exp(0.001109K_D^4 - 0.00569K_D^3 + 0.000625K_D^2 + 0.221K_D - 2.8 \tag{8}$$

Differences between Eq. (8) and the most recent DMT-based curve proposed in the literature (Marchetti 2016) are observed for K_D lower than 3 and higher than 6 (Fig. 2).

3 METHODOLOGY

To incorporate the effect of the fines content on the cyclic resistance ratio (*CRR*) of the soils as estimated via

DMT, the same approach proposed by Boulanger and Idriss (2014) is also adopted. According to these authors, CPT- and SPT-based empirical charts provide an estimation of the *CRR* as a function of a normalized soil resistance parameter, such as, for CPT, q_{c1Ncs} (as defined in Eq. 1) and, for SPT, $(N_1)_{60cs}$, which is the normalized number of blow counts corrected for energy ratio and fines content, as follows:

$$(N_1)_{60cs} = (N_1)_{60} + \Delta(N_1)_{60} \tag{9}$$

$$(N_1)_{60} = C_N \cdot N_{60} \tag{10}$$

$$m = 0.784 - 0.0768 \cdot (N_1)_{60cs}{}^{0.5} \tag{11}$$

$$\Delta(N_1)_{60} = \exp\left(1.63 + \frac{9.7}{FC + 0.01} - \left(\frac{15.7}{FC + 0.01}\right)^2\right) \tag{12}$$

where N_{60} is the energy-corrected blow count measured during SPT, C_N is the same of Eq. (3) and $\Delta(N_1)_{60}$ accounts for the beneficial effects of the fines content. Similar to CPT, the value of $(N_1)_{60cs}$ must be found by trial and error.

Both the normalized soil parameters $(N_1)_{60cs}$ and q_{c1Ncs} are obtained as sum of two components (see Eqs. 1 and 9): the first one considers the normalization of the measured data to the overburden stress, the second one accounts for the beneficial effect of the fines content, which is fictitiously translated into an increase of the soil resistance parameters $(N_1)_{60cs}$ and q_{c1Ncs}.

Following the above-mentioned approach, in this study the horizontal stress index corrected for the fines content, hereafter called $K_{D,cs}$, is calculated as:

$$K_{D,cs} = K_D + \Delta K_D \tag{13}$$

where K_D is already a normalized parameter and consequently saves its original definition, and ΔK_D is the increment of the horizontal stress index, calculated as a function of the fines content. In this study, the same functional form of Eq. (12) is adopted:

$$\Delta K_D = \exp\left(a + \frac{b}{FC + c} - \left(\frac{d}{FC + c}\right)^2\right) \tag{14}$$

where *a*, *b*, *c* and *d* are regression coefficients that need to be calibrated on experimental data.

Under the light of this new approach, the Eq. (8) can be generalized to all the different types of soils (not only clean sands), as follows:

$$CRR = \exp(0.001109 K_{D,cs}^4 - 0.00569 K_{D,cs}^3 + 0.000625 K_{D,cs}^2 + 0.221 K_{D,cs} - 2.8 \tag{15}$$

For the practical use of Eq. (13), a relationship able to express ΔK_D as a function of *FC* (Eq. 14) needs to be defined. Since the *FC* of the soils is rarely available during the execution of in-situ testing, an estimation of the fines content based on the material index I_D as obtained by DMT needs also to be preliminarily evaluated.

In this study, the above-mentioned relationships: *FC* as a function of I_D, and ΔK_D as a function of *FC*, are defined with reference to an Italian case study, where an extensive investigation program was performed after the 2012 Emilia earthquake. The large data set of experimental data obtained by both cyclic laboratory and in-situ tests, including both CPT and DMT, allowed the definition of previous FC-I_D and ΔK_D-FC relationships in a consistent manner.

4 CALIBRATION OF THE ADOPTED METHOD ON AN ITALIAN CASE STUDY

The considered case study is the river dyke of Scortichino, highly damaged by the 2012 Emilia earthquake (Tonni et al. 2015). In one of the investigated cross sections of the dyke one SDMT, one CPT and one borehole were performed down to 30 m depth. An undisturbed sample of silty sand was retrieved from the borehole between 6.20 ÷ 6.80 m depth and investigated in laboratory with a series of cyclic simple shear tests finalized to define the cyclic resistance curve of the soil. Laboratory experimentation showed that the soil deposit at that depth has a $FC = 40\%$ and a $CRR = 0.2$ at 15 cycles. On the side of the in-situ tests, an $I_D = 1.06$ and a $K_D = 2.1$ were measured during DMT at the mean depth of 6.40 m of the retrieved sample (Fig. 3).

4.1 *FC-I_D* relationship

Di Buccio et al. (2023) proposed a FC-I_D relationship for Emilia alluvial plain as follows:

$$FC = x_D(-31 I_D + 91) \tag{16}$$

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

For the site under study, the coefficient has been defined by imposing a $FC = 40\%$ for $I_D = 1.06$, which leads to $x_D = 0.7$ (Fig. 4).

4.2 ΔK_D-*FC* relationship

The Eq. (14) has been calibrated for the specific site by considering the silty sand deposit investigated in laboratory as a reference. Indeed, since the investigated specimen exhibited a $CRR = 0.2$ for 15 cycles, which approximately corresponds to a magnitude of 7.5, the related $K_{D,cs}$ value can be back-calculated from Eq. (15). Consequently, ΔK_D has been derived from Eq. (13) as equal to 3.26, and associated to the fines content of the specimen.

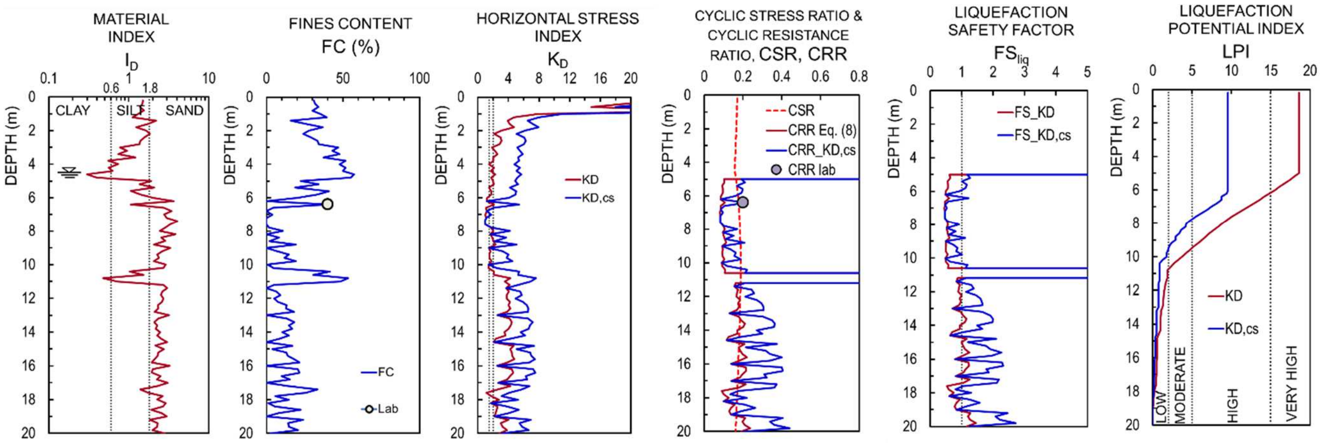

Fig. 3. Assessment of the soil liquefaction potential by adopting the DMT-based method proposed by Chiaradonna and Monaco (2022) (red lines) and that proposed in this study (blue lines).

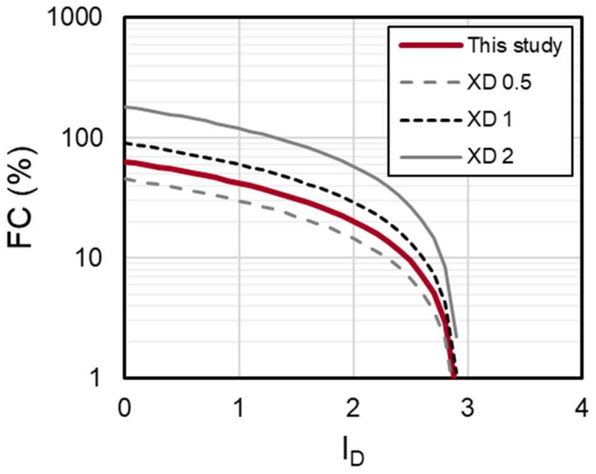

Fig. 4. FC-I_D relationship considered for the case study.

Since only one determination is available for this specific site, which is not enough to constrain all the coefficients of Eq. (14), the ΔK_D-FC relationship has been defined by assuming the b, c and d coefficients of Eq. (12) and by calibrating the coefficient a in order to obtain $\Delta K_D = 3.26$ for $FC = 40\%$. The obtained ΔK_D-FC relationship is:

$$\Delta K_D = \exp\left(1.33 + \frac{9.7}{FC + 0.01} - \left(\frac{15.7}{FC + 0.01}\right)^2\right) \tag{17}$$

also shown in Fig. 5.

4.3 Comparison between Chiaradonna and Monaco (2022) and the proposed methods

Fig. 3 compares the assessment of the soil liquefaction potential by adopting the proposed approach that accounts for the fines content effect and the previous one only for clean sand as proposed by Chiaradonna and Monaco (2022). The vertical profile of FC has been estimated through the Eq. (16) (Fig. 4) and the corrected $K_{D,cs}$ profile by applying the Eqs. (13) and (17) (Fig. 5).

The $K_{D,cs}$ significantly differ from the K_D between 1 m and 7 m depth from the ground surface, where the lowest values of I_D are measured and the higher fines content is expected, consequently.

For the liquefaction assessment, the considered seismic scenario is the May 20, 2012 mainshock, having moment magnitude $M_w = 6.1$ and epicentral distance R_{epi} = 7.5 km from the Scortichino site. An estimated maximum acceleration at the site of 0.26 g, equal to the recorded value at the recording station of Mirandola (D'Amico et al. 2020), has been also adopted in the cyclic stress ratio (CSR) computations according to the simplified expression reported by Boulanger and Idriss (2014).

The CRR estimated by Eq. (15) is generally higher than the CRR obtained without the fines correction and this leads to a higher safety factor against liquefaction along the soil column.

The "integral" liquefaction susceptibility at the test location has been finally 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 plots highlights remarkable differences in the first 10 m depth and a different classification of the soil liquefaction potential, moving from 'very high' to 'high' when the effect of the fines content is considered.

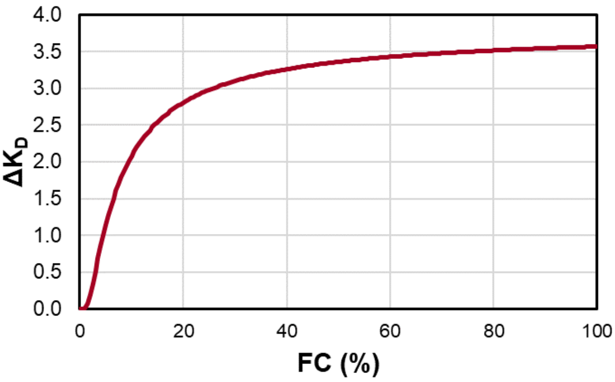

Fig. 5. ΔK_D-FC relationship considered for the case study.

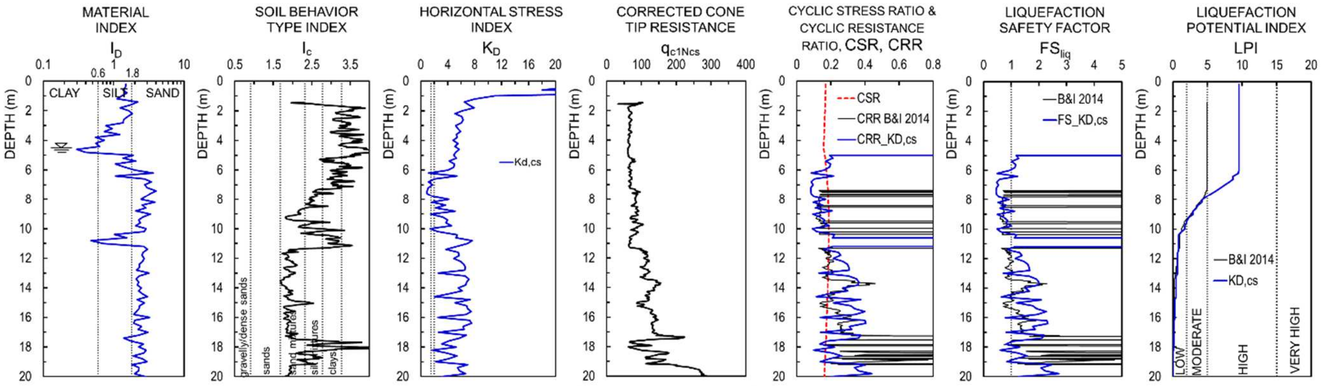

Fig. 6. Assessment of the soil liquefaction potential by adopting the DMT-based method proposed in this study (blue lines) and the CPT-based method by Boulanger and Idriss (2014).

4.4 Comparison between the proposed DMT-based and the CPT-based methods

Fig. 6 compares the assessment of the soil liquefaction potential by adopting the new DMT-based approach that accounts for the fines content effect and the CPT-based method as proposed by Boulanger and Idriss (2014).

The two independent approaches lead substantially to the same *LPI* profiles, except for the soil layer between 6 m and 8 m. This difference is due to the fact in this soil deposit the soil behavior type index I_c is higher than the cut-off value of 2.6, above which the soil is considered non-liquefiable. Conversely, the I_D profile evidences a soil behavior which can be assumed representative of a liquefiable soil. However, the experimentations performed in laboratory showed a clear susceptibility to soil liquefaction of that deposits, and confirmed as the characterization of intermediate soils is a challenging task that requires further studies.

5 CONCLUSIONS

This study proposed an upgrade of the existing methods for soil liquefaction assessment based on DMT by accounting for the beneficial effects of the fines content on the soil cyclic resistance.

The new approach allowed to reduce substantially the discrepancy of the obtained results when the CPT-based method proposed by Boulanger and Idriss (2014) is adopted.

The necessary relationships for the implementation of the fines correction have been defined for the Italian soil deposits affected by liquefaction after the 2012 Emilia earthquake, but future studies are necessary to confirm or disclaim the obtained results in different seismic and soil conditions.

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