Variability of the seismic response of a liquefiable soil with the fines content as estimated via dilatometer tests

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ABSTRACT

In the simplified methods for estimating the cyclic resistance ratio (CRR) based on the flat dilatometer test (DMT), the liquefaction triggering curve is defined as a function of the horizontal stress index. A DMT-based calibration of a simplified pore water pressure model for effective stress analyses has been also recently proposed by Chiaradonna et al. (2023), even though limited to an ideal clean sand.

This paper aims to explore the effects of the fines content on the seismic response of a liquefiable site where the cyclic strength of the soils is estimated by dilatometer tests. This evaluation is firstly performed on an ideal one-dimensional soil column, where the percentage of fines content is parametrically changed. Then, the study is verified on a real case, by considering a well-investigated site located in the Emilia-Romagna plain (Italy), where widespread liquefaction occurred in the 2012 seismic sequence. Indeed, a comprehensive site characterization from previous in-situ and laboratory tests carried out by various research groups is available for sand, silty sand, and sandy silt deposits encountered in that area. The nonlinear dynamic analyses accounting for the fines content effect are compared with that obtained by adopting the calibration procedure based on laboratory tests. Guidelines and limitations of the proposed approach obtained from this study are useful in providing awareness to practitioners about the calibration strategies for dynamic analysis based on DMT-tests.

Keywords: Liquefaction, Effective stress analysis, Excess pore water pressure.

1. Introduction

Recent studies have recognized the importance of effective stress dynamic analysis in estimating the seismic response of layered soils with a mixture of liquefiable and non-liquefiable soils (Cubrinovski et al. 2019). Two different approaches can be employed to perform effective stress analysis: (1) a 'loosely coupled' approach that predicts seismic-induced pore pressure increases by employing a simplified relationship used in conjunction with a constitutive model corresponding to total stress; (2) a 'fully coupled' approach that predicts both the stress-strain and pore water pressure response of soil using a plasticity-based effective stress constitutive model (Tropeano et al. 2019).

One of the main challenges in performing effective stress analysis is calibrating a constitutive model that can simulate dynamic soil behavior under seismic loading. To address this issue, a calibration procedure has been developed to define parameters for advanced constitutive models based on data from in-situ tests, such as cone penetration tests (CPT) (Ntritsos & Cubrinovski, 2020). Following this approach, the calibration of simplified stress-based pore pressure models, which were initially based solely on cyclic laboratory test data, was extended to include results from field tests commonly used in engineering practice (Chiaradonna et al. 2020, 2022).

More recently, Chiaradonna et al. (2023) extended the calibration procedure to the results of dilatometer tests (DMT). This calibration procedure is based on the liquefaction triggering chart based on DMT proposed by Chiaradonna & Monaco (2022) for clean sand. Consequently, the calibration procedure has the main drawback to be applicable only to clean sands.

In this study, the above calibration is upgraded to incorporate the effects of the fines content on the behavior of granular soils mixtures investigated by DMT, as proposed by Chiaradonna and Monaco (2024).

Section 2 briefly summarizes the steps for assessing the liquefaction potential of soils based on DMT results including for the fines content (FC) effects as proposed by Chiaradonna and Monaco (2024).

Section 3 recalled the simplified pore water pressure model and describes the DMT-based calibration of the model parameters.

Section 4 applies the upgraded calibration procedure to an ideal one-dimensional soil column and a real case study. The first case is used to show the effects of the fines contents on the seismic soil response when the percentage of FC is parametrically changed. The second case allows to test the quality of the match of the new calibration process by comparing it to the most traditional calibration based on the results of cyclic laboratory tests.

2. DMT-based liquefaction triggering method accounting for the fines content

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) was also adopted by Chiaradonna and Monaco (2024). According to the last Authors, the horizontal stress index was corrected for the fines content and calculated as:

$$K_{D,cs} = K_D + \Delta K_D \tag{1}$$

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, FC, as follows:

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

The Equation (2) was defined with reference to an Italian case study, where an extensive investigation program was performed after the 2012 Emilia earthquake.

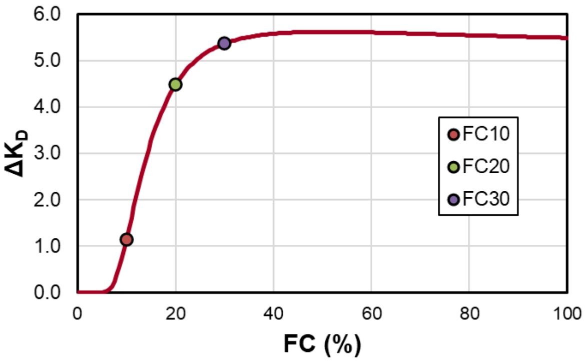

Figure 1. ΔK_D - FC relationship.

Under the light of this new approach, the liquefaction triggering curves proposed by Chiaradonna and Monaco (2022) can be generalized to all the different types of soils (not only clean sands), as follows (Figure 1):

$$\ln(\mathrm{CRR}) = a_4\, K_{D,cs}^4 + a_3\, K_{D,cs}^3 + a_2\, K_{D,cs}^2 + a_1\, K_{D,cs} + a_0$$

where:

$$\begin{aligned} a_4 &= 0.001109 \\ a_3 &= \text{-}0.00569 \\ a_2 &= 0.000625 \\ a_1 &= 0.221 \\ a_0 &= -2.8 \end{aligned} \tag{3}$$

As shown in figure 2, for each point on the CRR - $K_{D,cs}$ curve there is a corresponding point on the CRR - N plane for several cycles for a representative moment magnitude earthquake of $M_W = 7.5$. The point can be further multiplied for the MSF and K_σ, according to the formulation proposed by Boulanger and Idriss (2014), to obtain a cyclic resistance curve in the CRR-N plane. Therefore, it is possible to generate a cyclic resistance curve for each specific $K_{D,cs}$ selected from Figure 2a.

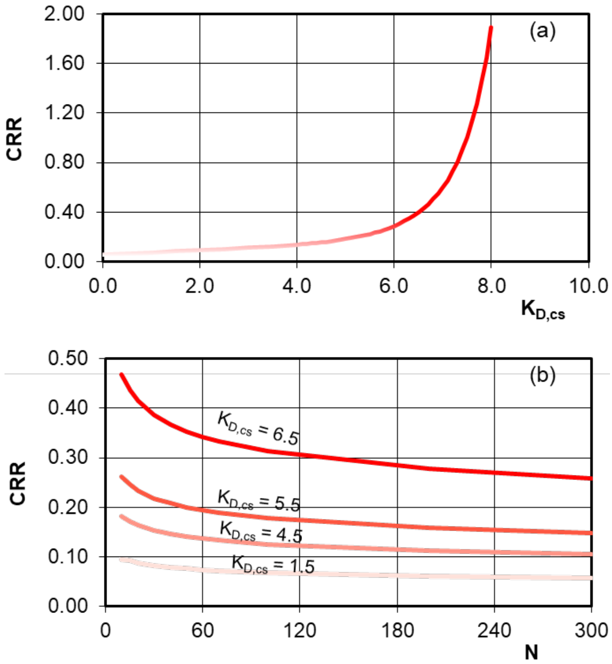

Figure 2. Cyclic resistance curve from the empirical K_D - based chart and σ' = 50 kPa: (a) CRR - $K_{D,cs}$ threshold curve; (b) set of cyclic resistance curves for $K_{D,cs}$ ranging from 1.5 to 6.5.

An example of the generated curves for an effective stress of 50 kPa is shown in Figure 2b.

Further details on the generation of CRR - N curves starting from the DMT-based triggering curve can be found in Chiaradonna et al. (2023).

3. Key features of the simplified pore pressure model and DMT-based calibration

Chiaradonna et al. (2016; 2018; 2019) proposed a stress-based pore water pressure model that allows for the comparison of irregular seismic loading with soil liquefaction resistance. The model uses an incremental variable κ, called 'damage parameter', which is a function of the applied load and considers the cyclic strength of the soil. The cyclic resistance curve is described analytically by the equation (Figure 3):

$$\frac{\mathrm{CRR}-\mathrm{CSR}_t}{\mathrm{CSR}_r-\mathrm{CSR}_t} = \left(\frac{15}{N}\right)^{\frac{1}{\alpha}} \tag{4}$$

CRR is defined as the ratio between the amplitude of shear stress and the initial effective confining pressure; N represents the number of cycles, CSRr is the value of CRR for the reference number of cycles (which is typically equal to 15 cycles) and CSR_t represents the limit of CRR as N approaches infinity.

For a regular shear stress history, the ratio between the excess pore pressure and the initial effective confining pressure, r_u, can be expressed as a function of the number of cycles, N, like that proposed by Chiaradonna et al. (2018):

$$r_u = a\left(\frac{N}{N_L}\right)^b + (0.95-a)\left(\frac{N}{N_L}\right)^d \tag{5}$$

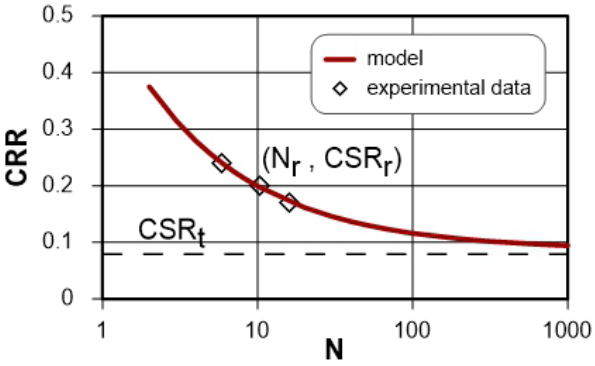

Figure 3. Cyclic resistance curve according to the model.

Where N_L is the number of cycles at which liquefaction phenomena occur and a, b and d are the shape parameters the curve. The latter can also be defined as a function of the relative density and fines content (Chiaradonna et al. 2020).

The above-described pore pressure model has been implemented in the non-linear code SCOSSA (Tropeano et al. 2016). SCOSSA models the soil profile as a system of consistent lumped masses connected by viscous dampers and springs with hysteretic behavior. The MKZ model and modified Masing rules describe the non-linear shear stress-strain relationship. For more information on the numerical implementation, refer to Tropeano et al. (2019).

Chiaradonna et al. (2020) proposed a straightforward definition of the parameters of the curve CRR - N (Eq. 4): CSR_r can be computed as a function of the effective stress state and the normalized and corrected cone tip resistance, q_{c1Ncs}, of the CPT. The parameters α and CSR_t are only dependent onq_{c1Ncs}. This approach allows for the cyclic strength to be easily defined based on the results of CPT_s.

3.1. DMT-based charts for the calibration of the model parameters

The cyclic strength parameters in Eq. (4) were evaluated by applying a non-linear regression analysis to a dataset of generated curves for $K_{D,cs}$ ranging from 1.5 to 6.5 and a mean initial effective stress, σ', ranging from 50 to 800 kPa, according to the procedure described in section 1. The obtained model parameters (α, CSR_r and CSR_t) were then expressed as a function of the initial stress state, σ'_{m0}, and soil strength evaluated from DMT, (i.e., $K_{D,cs}$).

The procedure for calibrating the cyclic strength parameters of the pore water pressure model on the generated cyclic resistance curves is divided into two steps.

The first step involved the calibration of α and CSR_t, while the second step involves calibrating of CSR_r, which refers to 15 cycles. With reference to the calibration of α, the parameter governing the steepness of the cyclic resistance curves the parameter is ruled only by $K_{D,cs}$.

Figure 4a shows that the relationship is accurately described by a third-degree polynomial equation. CSR_t is defined as the shear stress ratio, CRR, of the generated curves corresponding to one million of cycles. Figure 4b plots the threshold values CSR_t as a function of $K_{D,cs}$ for different values of effective stress, σ'.

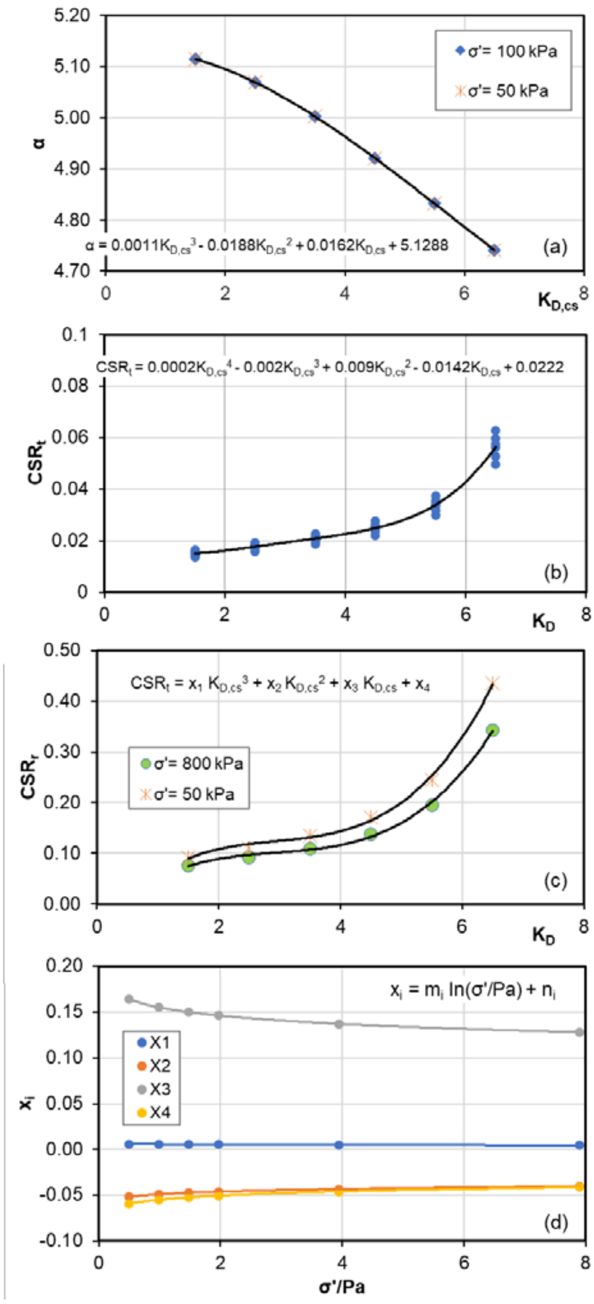

Figure 4. DMT-based charts for model parameter calibration

Since the shear stress ratio are small, the effect of σ'_{m0} was neglected and a polynomial expression was used to model CSR_t (Figure 4b).

The CRR values of the dataset of the generated curves for $N = 15$, i.e., CSR_r, were plotted against σ'_{m0} and $K_{D,cs}$ (Figure 4c). The CSR_r points were then interpolated using a polynomial expression shown in Figure 4c, where the coefficients, x_1, x_2, x_3 and x_4 are determined by (σ'/p_a), where p_a represents the atmospheric pressure (Figure 4d). The coefficients, m_i and n_i, of the logarithmic function were determined through a non-linear regression analysis. These values are listed in Table 1.

Table 1. Equation coefficients for the calculation of x_i

Coefficient	x_1	x_2	x_3	x_4
m_i	5×10^{-4}	0.0041	-0.013	0.0065
n_i	0.0056	-0.049	0.155	-0.0549

4. Application of the proposed method

4.1. Parametric study on an ideal case

The proposed DMT-based calibration procedure has been evaluated on an ideal 1D soil column. The considered soil column is the ideal case provided in iteration 1 of the Licorne project (benchmark of the Working Group on liquefaction Phenomena organized by the French Permanent Accelerometric Network – RAP - Committee; https://rap.resif.fr), as described in Khalil et al. (2022). It consists of two layers: 6 m dense sand with a relative density, D_r, close to 70%, below 4 m loose sand with $D_r \approx 40\%$, designated as “mat 1” and “mat 2” respectively. The groundwater table (g.w.t.) is 1 m below the surface.

Figure 5a shows the soil column geometry and the assigned vertical shear wave velocity profile, V_S. The soil properties for dynamic analyses are shown in Figure 5b where the laboratory data (symbols) are fitted with the MKZ model implemented in the SCOSSA code.

For the dense sand, mat1, the calibration of the stress-based model was performed on the cyclic triaxial tests artificially generated by an advanced constitutive model by Khalil et al. (2022). Further details on the model can be found in Khalil et al. (2022) and Chiaradonna et al. (2023).

For the loose sand, mat2, the calibration of the cyclic resistance curve was performed according to the proposed DMT-based procedure, where the $K_{D,cs}$ value used to enter inside charts of Figure 3 were obtained by parametrically changed the fines contents from 0 to 30%. The K_D in Equation (1) was estimated with the relationships proposed by Jamiolkowski et al. (2001) as function of the relative density, which was 2.17 for the considered case. ΔK_D was obtained from Equation 2 by parametrically ranging the fines contents from 0 to 30%.

Figure 6 shows the comparison among the obtained cyclic resistance curves used in the analysis. Table 2 also lists the numerical values of the model parameters.

The obtained trend is ruled by the ΔK_D - FC curve reported in Figure 1. Indeed, for FC equal to 0 and 10% the increment of the K_D is quite limited, while for FC equal to 20% and 30% there is a significant increase in the cyclic strength.

The cyclic triaxial data provided by Khalil et al. (2022) were used to define the r_u - N/N_L relationship for both soils (Chiaradonna et al. 2023).

The seismic bedrock was assumed to be a rigid and the input motions were applied as inside motions at the base of the soil column.

A set of dynamic analyses were performed by considering the different curves of Figure 6 for mat.2 and by applying at the base of the soil column the ‘pulse-like’ motion whose response spectrum is shown in Figure 7.

Figure 8 shows the results of the numerical simulations in terms of vertical profiles of maximum acceleration, shear strain, stress, and excess pore pressure ratio.

Similarly to the cyclic curves, the profiles of pore water pressure ratio are governed by the ΔK_D - FC curve reported in Figure 1. Indeed, for FC equal to 0 and 10% the liquefaction is attained in the mat2 layer. Conversely, for FC 20% and 30%, the generated pore pressure ration is less than 0.3. A limited variability is observed in the other vertical profiles.

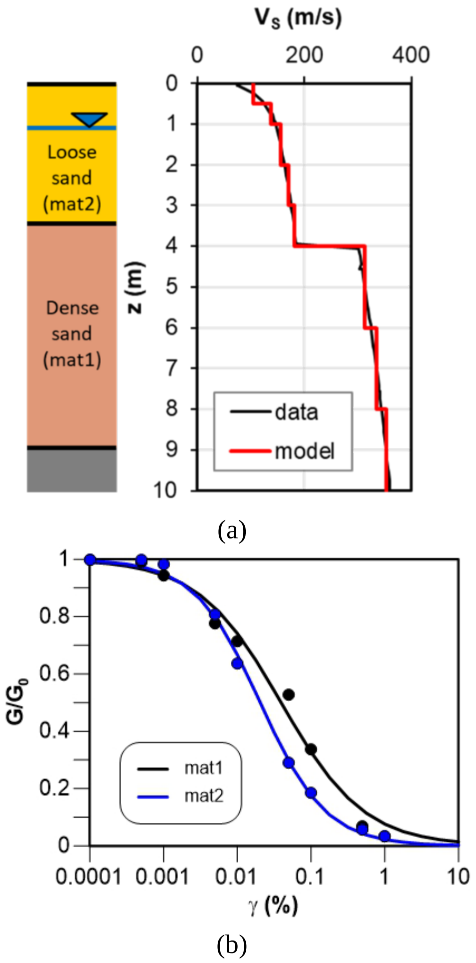

Figure 5. (a) Ideal soil column and (b) normalized shear modulus vs. shear strain for mat1 and mat2 and analytical curves adopted in the analyses (MKZ model)

Table 2. Model pore water pressure parameters.

FC (%)	ΔK_D	$K_{D,cs}$	CRR	α	CSR_r	CSR_t
0	0	2.17	0.095	5.087	0.116	0.016
10	0.85	3.02	0.112	5.036	0.131	0.016
20	3.32	5.487	0.222	4.833	0.272	0.010
30	3.97	6.143	0.314	4.774	0.385	0.013

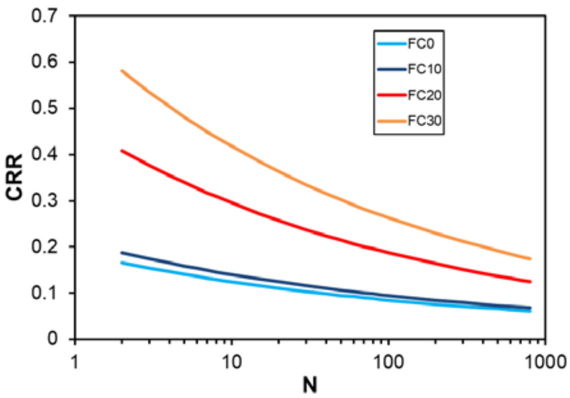

Figure 6. DMT-based cyclic resistance curves for different fines content.

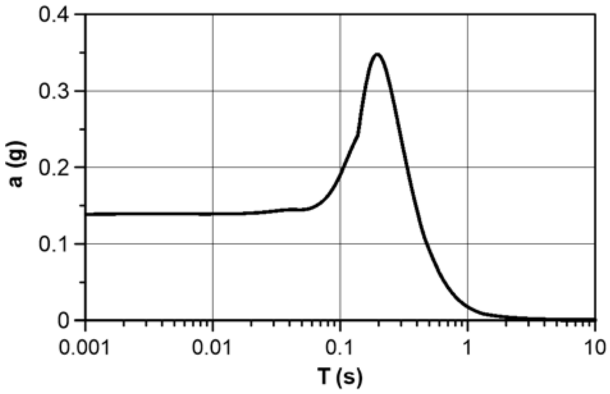

Figure 7. Input motion.

4.2. Verification on a case study

In-situ and laboratory geotechnical investigation carried out after the earthquake at the Scortichino site, allowed the definition of an accurate subsoil model for the dynamic analyses (Tonni et al. 2015, Chiaradonna et al. 2016, 2019). Figure 10 shows the soil layering and the related shear wave velocity profile, as obtained by analyzing the borehole logs and geophysical tests. The core of the dike (AR) and its foundation soil (B) consist of silty sand, while a thick formation of alluvial sands (A), interbedded by clay (C), overlies an alternation of both materials (AL) and the bedrock.

Resonant column and cyclic simple shear tests were carried out (Tonni et al. 2015) to obtain the variation of the normalized shear modulus, G/G_0, and damping ratio, D, with the shear strain, γ, required to simulate the non-linear and dissipative dynamic soil behaviour, as reported in Chiaradonna et al. (2019).

Chiaradonna et al. (2019) performed the 1D stress dynamic analysis of the considered soil column, calibrated the PWP model on the available cyclic direct simple shear tests carried out on soils (A) and (B).

The parameters of the cyclic resistance curve used in the present study have been calibrated for the soil (B) by using the proposed calibration procedure by considering FC = 40% as detected by the experimental investigations. The available DMT led to a of $K_{D,cs}$ equal to 5.40 for an effective stress, σ' of 109 kPa. These two parameters have been used to enter charts of Figure 4 and define the model parameters reported in Table 3.

Figure 9 reports the comparison between the cyclic resistance curve adopted in the analysis for the silty sand (B), which has been obtained via the application of the relationships reported in Figure 4, and that experimentally defined through the cyclic laboratory tests. The same comparison is shown in Table 3 in terms of model parameters. The prediction of the cyclic strength via DMT is slightly higher than that measured in laboratory.

The deconvolved motion of the May 20, 2012, main-shock recorded at the Mirandola station (MRN) has been assumed as reference input motion for the analysis (Chiaradonna et al. 2019). The input was applied as an outcrop motion at the bedrock, which was modelled as a deformable medium with shear wave velocity V_S = 800 m/s.

The results of the effective stress analysis are reported in Figure 10 in terms of vertical profiles of the maximum excess pore pressure ratio. Figure 10 reports also the vertical r_u profile obtained by Chiaradonna et al. (2019), where the cyclic strength of the layer (B) was directly defined on the cyclic laboratory test results.

Table 3. Model pore water pressure parameters.

Calibration	α	CSR_r	CSR_t	N_r
DMT-based	4.84	0.24	0.01	15
Lab-based	1.85	0.24	0.078	5.9

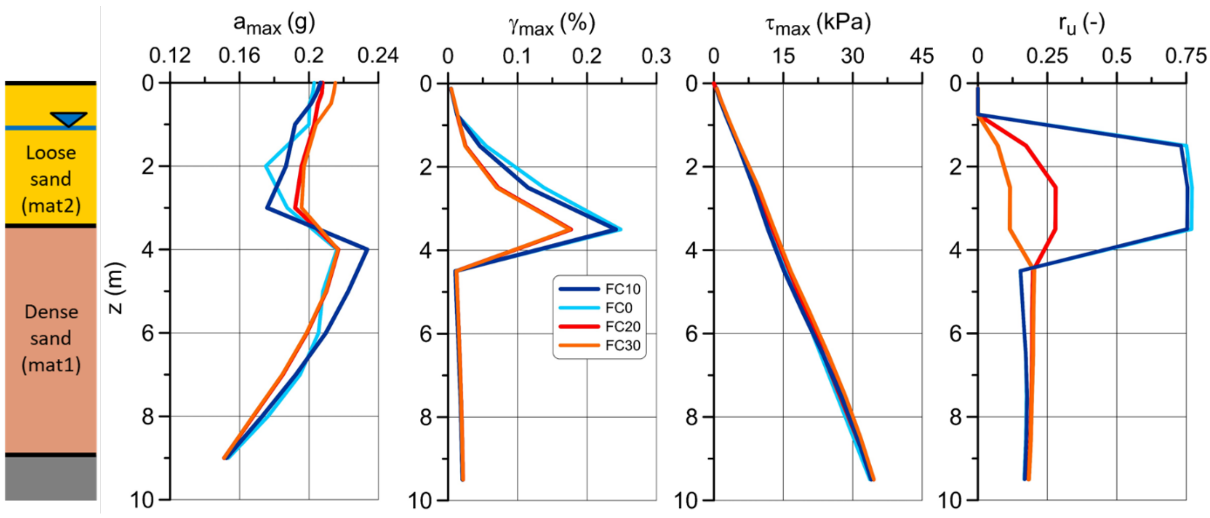

Figure 8. Results of the parametric study on the ideal soil profile.

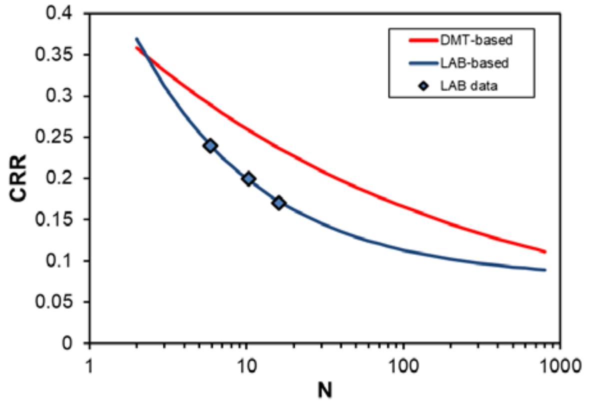

Figure 9. Cyclic resistance curves for the soil (B) as predicted by the proposed approach and measured in laboratory.

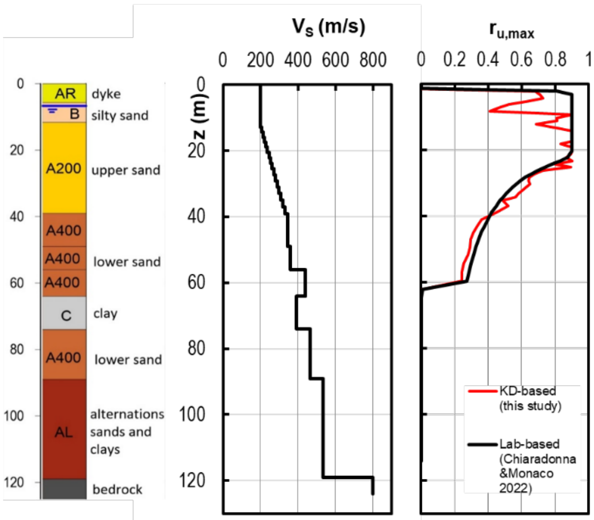

Figure 10. Vertical profile of the shear wave velocity and the maximum excess pore pressure ratio obtained by the dynamic analyses in effective stress for the considered Scortichino site.

The analysis where the cyclic strength of the B soil was based on the DMT empirical curve provides less r_u in the first 10 m and similar results after 10 m compared to the laboratory-based calibration of the cyclic strength (Figure 10), even though higher irregularity in the profile is due to higher numerical instability.

5. Discussion and conclusion

The DMT-based empirical curve for liquefaction triggering proposed by Chiaradonna and Monaco (2024) accounts for the effect of fines content on the cyclic resistance of soils. This curve was used to calibrate a simplified model for predicting the pore water pressure build-up induced by seismic loading. Consequently, the effect of fines is implicitly included in the calibration of the model parameters. The use of the charts provided in Figure 4 allows also a prompt definition of the cyclic strength of sands to be used in effective stress analysis.

The calibration procedure has been applied to an ideal one-dimensional soil column and a real case study. The first case was used to show that the effects of the fines contents on the seismic soil response is strongly dependent from the assumed ΔK_D - FC relationship (Figure 1). The second case allowed to verify the quality of the new calibration process on a real case, which led to results like those obtained via the model calibration based on cyclic laboratory tests.

The main drawback of the proposed approach is related to the high sensitivity of the results to the shape of the ΔK_D - FC relationship. This issue will be addressed in future studies, based on field data from different test sites.

6. Acknowledgements

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