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Numerical quantification of the dependency of the seismic site response on the DMT-based cyclic strength of sands

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ABSTRACT: Recent studies recognized the importance of performing dynamic analyses in effective stress conditions for assessing the liquefaction potential of sites, especially due to the limitations of the existing methods based on empirical charts. Indeed, these latter are not able to consider the interaction among soil layers and the dissipation/redistribution of the seismically induced excess pore water pressure during and after the shaking. In this paper, a simplified stress-based pore water pressure model implemented in a non-linear computer code was considered. The calibration of the model, originally based only on cyclic laboratory test data, was generalized to include the results of field tests commonly used in engineering practice, such as the results of the flat dilatometer test (DMT). The proposed calibration approach was verified by performing effective stress dynamic analysis of an ideal 1D soil column. The soil profile consists of a 4m-thick loose sand layer overlying a 6m-thick dense sand. Also, cyclic resistance curves numerically generated with an advanced constitutive model are adopted for comparison. Dynamic analyses in effective stress for different shaking intensities are performed with the scope to quantify the dependency of the site response on the cyclic strength of soils.

Keywords: Liquefaction; Effective stress analysis; Excess pore water pressure; DMT; Calibration

1 INTRODUCTION

Recent research recognized the importance of effective stress dynamic analysis in estimating the seismic response of layered soil profiles with interbedded liquefiable and non-liquefiable soils (Cubrinovski et al., 2019).

Two distinct approaches can be adopted to perform an effective stress analysis: (1) a 'loosely coupled' approach that predicts seismic-induced pore pressure build-up by adopting simplified relationships used in combination with constitutive models that address total stress (e.g., pore pressure prediction based on accumulated strains or stresses), and (2) a 'fully coupled' approach that uses a plasticity-based effective stress constitutive model to predict both the stress-strain and the pore pressure response of the soil (Tropeano et al., 2019).

One of the key challenges in performing effective stress analysis is the calibration of constitutive models able to simulate the dynamic soil behaviour under seismic loading. To overcome this problem, calibration procedures have been developed to guide the definition of the parameters of advanced constitutive models based on data from in-situ tests, such as Cone Penetration Test - CPT (Ntritsos and Cubrinovski, 2020). Following this philosophy, the calibration of a simplified stress-based pore water pressure model, originally based only on cyclic laboratory test data, has been generalized to include the results of field tests commonly used in engineering practice (Chiaradonna et al. 2020, 2022).

In this study, the above-mentioned calibration procedure is extended to the results of dilatometer test, DMT.

2 BACKGROUND ON THE ASSESSMENT OF THE CYCLIC STRENGHT OF SANDS VIA DMT

Chiaradonna and Monaco (2022) updated the cyclic strength estimation based on flat dilatometer to the most recent framework proposed by Boulanger and Idriss (2014), as shown in Figure 1a. To each point of the curve CSR-K_D corresponds a point in the CSR-N plane for a number of cycles representative of a moment magnitude $M_W = 7.5$ (usually around 15 cycles), which can be furtherly multiplied for the MSF and K_σ, according to formulation proposed by Boulanger and Idriss (2014), in order to obtain a cyclic resistance curve in the plane CSR-N. This implies that for each specific K_D value selected from Figure 1, it is possible to generate a cyclic resistance curve.

2.1 *Cyclic resistance curves generated from the empirical relationship based on K_D*

In this study, by using this CSR-K_D relationship (Fig. 1a), a set of cyclic resistance curves (CSR, N) has been generated for K_D ranging from 1.5 to 6.5 and a mean initial effective stress, σ', ranging from 50 to 800 kPa. An example of the generated curves for an effective stress equal to 50 kPa is reported in Figure 1b.

The analytical expressions to move from Figure 1a to 1b are the same detailed in Chiaradonna et al. (2020).

It is worth highlighting here that, the methodology here suggested for the definition of cyclic resistance curves can be straightforward used for the calibration of constitutive models used in effective stress analysis for liquefaction problems, as for example shown in Ntritos and Cubrinovski (2020) and Chiaradonna et al. (2022) on the results of cone penetration tests.

In this study, the dataset of the cyclic resistance curves shown in Figure 1b is used for the calibration of a simplified pore stress-based pore water pressure model.

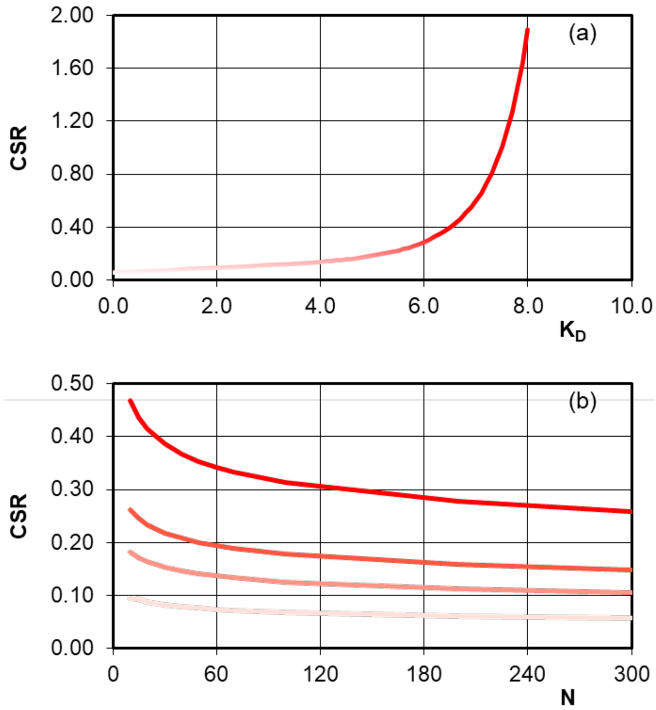

Figure 1. Generated cyclic resistance curve from the empirical K_D-based chart and σ'=50 kPa: (a) CSR-K_D threshold curve proposed by Chiaradonna and Monaco (2022); (b) set of cyclic resistance curves generated for K_D ranging from 1.5 to 6.5.

3 SUMMARY OF THE KEY FEATURES OF THE SIMPLIFIED PORE PRESSURE MODEL

A simplified stress-based pore water pressure model, proposed by Chiaradonna et al. (2016, 2018) permits the comparison of the irregular seismic loading with the soil liquefaction resistance, through an accumulation stress-based variable κ, called 'damage parameter'. It is an incremental function of the applied load that considers the cyclic strength of the soil. This latter is expressed in terms of cyclic resistance curve, analytically described by the equation:

$$\frac{(CSR - CSR_t)}{(CSR_r - CSR_t)} = \left(\frac{15}{N_L}\right)^{\frac{1}{\alpha}} \quad (1)$$

where CSR is the shear stress amplitude normalized by the initial effective confining pressure; N_L is the number of cycles at liquefaction, CSR_t is the asymptotic value of CSR as the number of cycles tends to infinite, CSR_r is the ordinate of the curve for $N_L = 15$ (usually adopted as a reference number of cycles). The model adopts a criterion for which liquefaction is attained when r_u (ratio between the excess pore pressure and the initial effective confining pressure) exceeds 0.95. For a regular shear stress history, κ is proportional to the number of cycles, N; it is, therefore, possible to express the pore pressure ratio, r_u, as a function of the number of cycles, through the relationship proposed by Chiaradonna et al. (2018):

$$r_u = a\left(\frac{N}{N_L}\right)^b + (0.95 - a)\left(\frac{N}{N_L}\right)^d \quad (2)$$

where a, b and d are best-fitting parameters that control the shape of the curve.

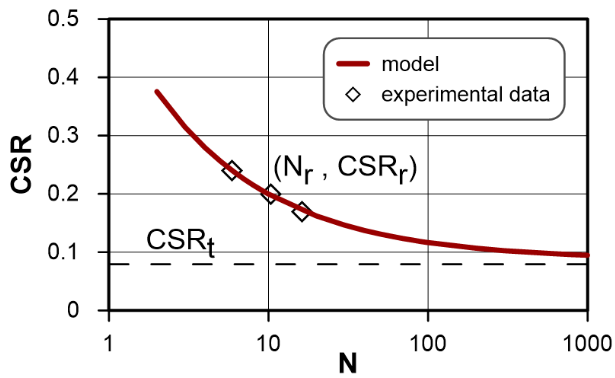

Figure 2. Cyclic resistance curve according to the model

The pore pressure model has been implemented in the non-linear code SCOSSA (Tropeano et al., 2016) which models the soil profile as a system of consistent lumped masses, connected by viscous dampers and springs with hysteretic behaviour. The non-linear shear stress-strain relationship is described by the MKZ model and the modified Masing rules. More details about the numerical implementation can be found in Tropeano et al. (2019).

Chiaradonna et al. (2020) proposed a straightforward definition of the parameters of the curve CSR-N (Eq. 1): 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; while α and CSR_t are just function of q_{c1Ncs}. In so doing, the cyclic strength can be easily defined directly on the results of CPTs.

4 PROPOSED CALIBRATION PROCEDURE

The cyclic strength parameters to define Eq. (1) were defined for all the dataset of curves generated in section 2.1 (Fig. 1b) using non-linear regression analysis. Then, the obtained model parameters (α, CSR_r and CSR_t) were expressed as a function of the initial stress state, σ'_{mo}, and soil strength evaluated from DMT, i.e., K_D.

4.1 DMT-based charts for defining the model parameters for sands

The calibration procedure of the cyclic strength parameters of the pore water pressure model on the generated cyclic resistance curves has been divided into two steps: the first step is related to the calibration of α and CSR_t, while the second one is related to the calibration of CSR_r, which refers to 15 cycles.

With reference to the calibration of α, governing the steepness of the cyclic resistance curves the parameter is ruled only by K_D. As shown in Figure 3a, the relationship is well described by a third-degree polynomial equation.

CSR_t was defined as the shear stress ratio of the generated curves corresponding to one million of cycles. The threshold values CSR_t, were plotted in Figure 3b as a function of K_D for different values of effective stress, σ'.

Due to the small values of shear stress ratio, the effect of σ' was neglected and a polynomial expression was adopted for modelling CSR_t (Fig. 3b).

Cyclic Stress Ratios of the dataset of the generated curves for N = 15, i.e., CSR_r, were plotted as a function of σ'_{mo} and K_D (Fig. 3c). Hence, the CSR_r points were interpolated with a polynomial expression expressed in Figure 3c, where the coefficients, x_1, x_2, x_3 and x_4 are ruled by (σ'/Pa), where Pa is the atmospheric pressure (Pa = 101.3 kPa), with a logarithmic function (Fig. 3d). The coefficients, m_i and n_i, of the relationships in Figure 3d were defined through a non-linear regression analysis and are reported in Table 1.

Table 1. Coefficients of the equations 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

5 EVALUATION OF THE DMT-BASED PROCEDURE

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 below 4 m loose sand, designated as "mat1" and "mat2" respectively. The groundwater table (g.w.t.) is 1 m below the surface. Figure 4 shows the soil column geometry and the assigned vertical shear wave velocity profile, V_S, while the soil layer properties are reported in Table 2. Both soil layers are considered ideal clean sands, inspired by the well-investigated Toyoura sand.

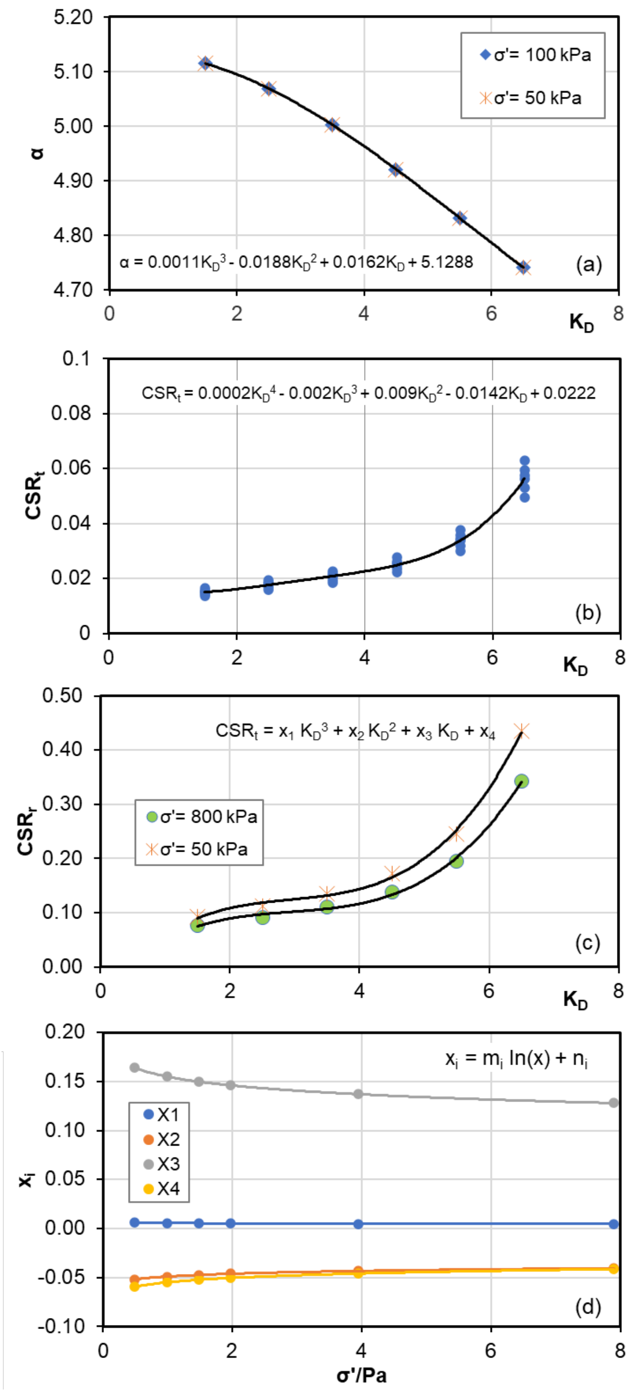

Figure 3. DMT-based charts for model parameter calibration

To characterize the soil behavior, laboratory tests were artificially generated by an advanced constitutive model for liquefaction by Hujeux (1985), implemented in the code GEFDyn (Aubry and Modaressi, 1996). The simulated tests include undrained triaxial tests, cyclic triaxial tests to define the cyclic resistance curves, and cyclic torsional tests to define the normalized shear modulus, G/G_0, and damping ratio, D, as a function of the shear strain, γ.

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.

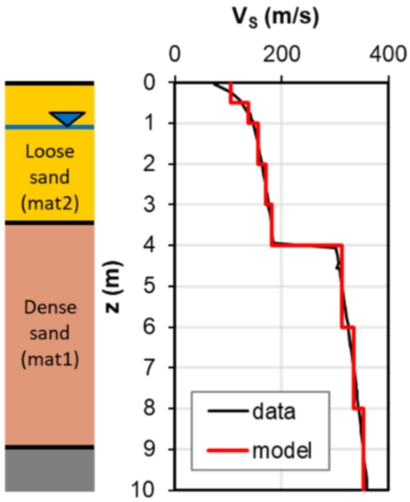

Figure 4. 1D ideal soil column

The soil column was discretized in sublayers with the thickness variable between 0.5 m and 1 m, and the mean value of the shear wave velocity profile was assigned to each layer. The non-linear and dissipative soil behavior was modeled through the parameters of the MKZ model and modified Masing rules, according to Tropeano et al. (2016, 2019) on the provided data (Fig. 5). For the dense sand, mat1, the calibration of the stress-based model was also performed on the provided cyclic triaxial tests (Table 3).

For the loose sand, mat2, the calibration of the cyclic resistance curve was performed according to the proposed DMT-based procedure, the CPT-based procedure described by Chiaradonna et al. (2020) and Khalil et al. (2022). For the DMT-based calibration, the K_D value used to enter inside charts of Figure 3 was estimated with the relationships proposed by both Jamiolkowski et al. (2001) and Reyna and Chameau (1991), hereafter labelled as 'Jam' and 'R&C', which was 2.17 and 1.73, respectively. Figure 6 shows the comparison among the obtained cyclic resistance curves used in the analysis. The data provided by Khalil et al. (2022) were used to define also the r_u - N/N_L relationship (Table 3).

Table 2. Properties of the soil layers (Khalil et al., 2022)

Soil layer	Solid density (kg/m^3)	Porosity	Relative density (%)	Hydraulic conductivity (m/s)
mat2	2700	0.35	40%	0.0001
mat1	2700	0.35	70%	0.00001

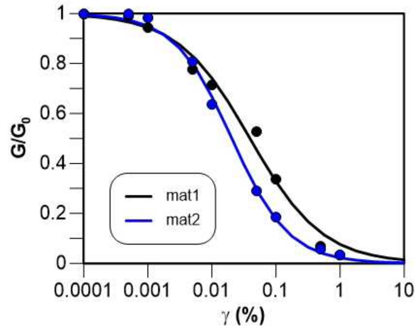

Figure 5. Normalized shear modulus vs. shear strain for mat1 and mat2 and analytical curves adopted in the analyses

Table 3. Model parameters used in the simulations

Soil layer	α	CSR_t	CSR_r	a	b	d
mat1	1.353	0.024	0.176	0.66	0.7	4
mat2 (CPT)	3.021	0.003	0.116	1.06	0.5	4
mat2 (DMT-R&C)	5.448	0.015	0.099	1.06	0.5	4
mat2 (DMT-Jam)	5.454	0.016	0.108	1.07	0.5	4

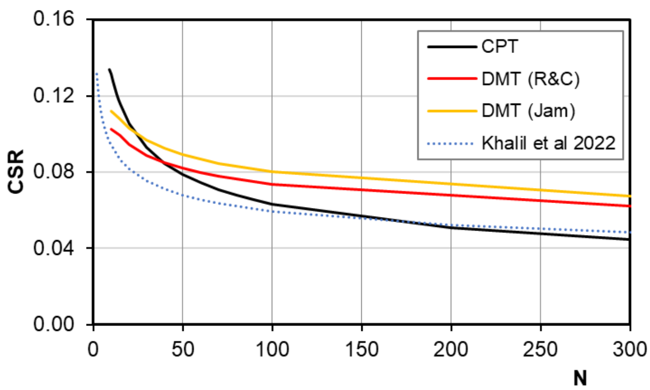

Figure 6. Cyclic resistance curves assigned to mat2 in the analyses according to the CPT-, DMT-based calibration for two different Dr-K_D relationships, and Khalil et al. (2022)

5.1 *Comparison with the CPT-based chart for the calibration of the model parameters*

A first comparison among the CPT and the DMT-based (both R&C and Jam) procedures for the definition of the cyclic strength of soils was performed by applying at the base of the soil column the 'pulse' motion 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.

The profiles show a limited variability, except for the loose sand layer where the major differences are detected in the acceleration, shear strain and pore pressure. At 3 m depth, CPT and DMT (Jam) lead to similar results respect to DMT (R&C) because the related cyclic resistance curves (Fig. 6) are closer for a low number of cycles.

However, due to the similarity of the response between the DMT (Jam) and the DMT (R&C) calibration, only the last one was considered in a more general comparison with the simulations reported by Khalil et al. (2022).

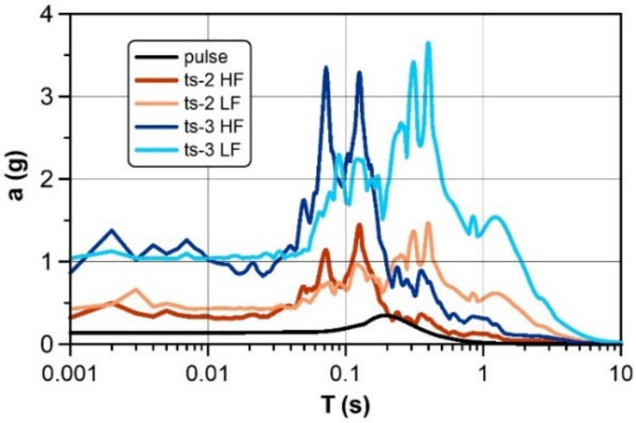

Figure 7. Adopted input motions

5.2 *Comparison with the predictions provided by Khalil et al. (2022)*

Khalil et al. (2022) report the results of the first iteration of the LICORNE (Liquefaction and Cyclic mObility Representation on Numerical Experiments) project, aiming to assess the effect of both, the pore water pressure onset and the liquefaction occurrence.

For the LICORNE benchmark, 11 teams participated with computers codes implementing both loosely coupled and fully coupled effective stress models.

Khalil et al. (2022) tested the considered soil column for high frequency and low frequency content motions (so called Ts HF and Ts LF). Five of those (Fig. 7) were also considered in this study for comparison with the DMT (R&C)-based calibration procedure.

Figure 9 show the profiles of the maximum pore pressure attained during the analyses performed by considering the DMT (R&C) calibration and the results of the simulations reported in Khalil et al. (2022). These latter are classified in different groups (B, C,… I) that share similar soil constitutive models, e.g., H and B are related to a loosely coupled approach like in SCOSSA, while the others are related to fully coupled approaches. For very intense input motions (3 LF and HF), the DMT (R&C) approach leads to the liquefaction of the entire profile, as observed also for the simulation of the group B. For less intense motions (2 LF, 2 HF and pulse), it is possible to observe a higher discrepancy among the results. The DMT (R&C) approach overestimates the maximum pore pressure on both low and high frequency contents and also in the loose sand deposit in the case of the pulse motion.

6 DISCUSSION AND CONCLUSIONS

The K_D-based empirical curve for liquefaction triggering proposed by Chiaradonna and Monaco (2022) was used to calibrate a simplified model for predicting the pore water pressure build-up induced by seismic loading. The use of the charts provided in Figure 3 allows a prompt definition of the cyclic strength of sands to be used in effective stress analysis.

The comparison with the simulations performed on several computer codes in the framework of the Licorne project, shows that the considered model leads to conservative estimation of the pore water pressure for low/high intensity of the ground motions, which is tolerable in the use of a simplified approach.

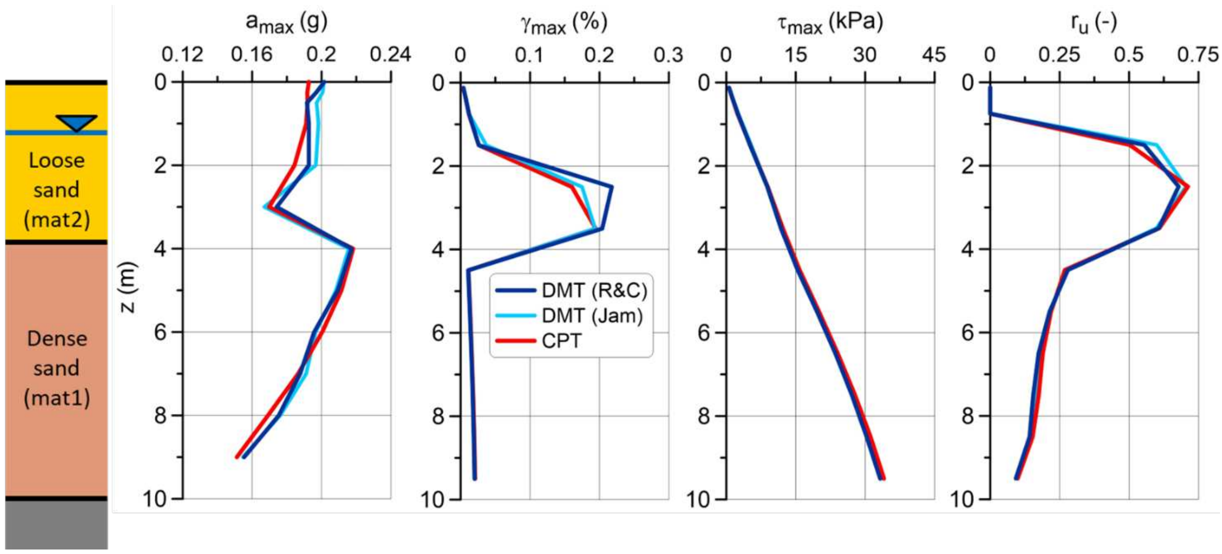

Figure 8. Comparison of the results of the analyses in terms of vertical profiles of maximum acceleration, shear strain, shear stress and pore pressure ratio obtained for CPT and DMT-based calibration procedures

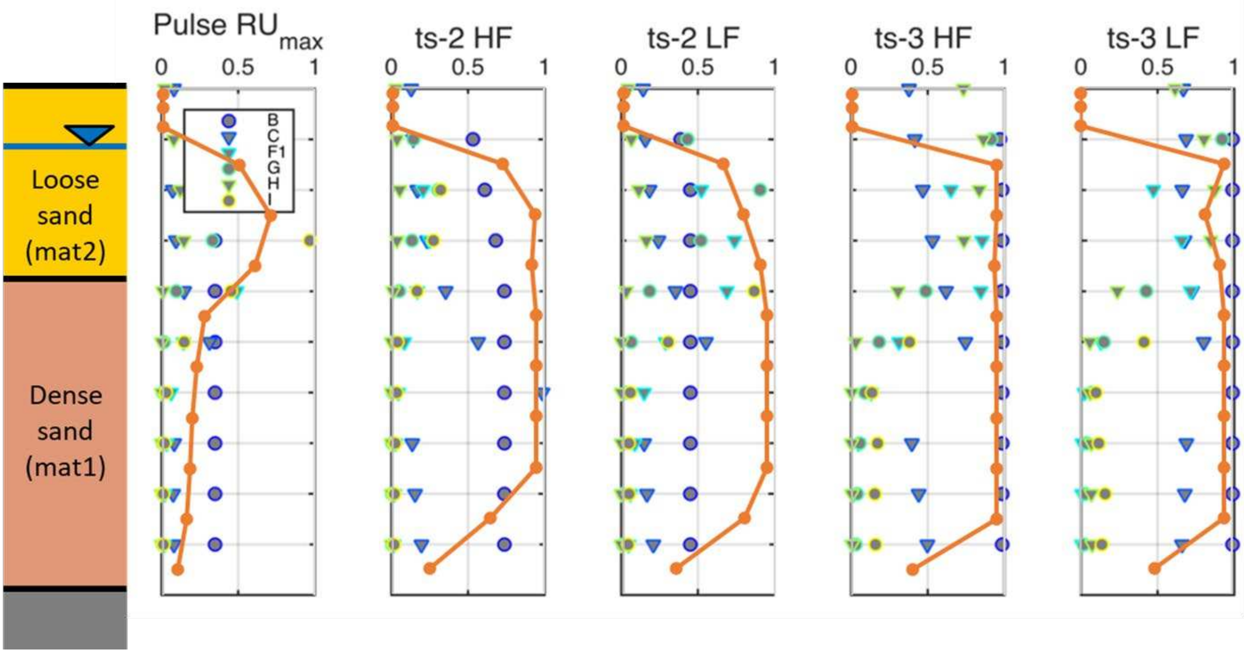

Figure 9. Vertical profiles of the maximum pore pressure ratio for the 5 considered input motions as obtained by the DMT-based calibration procedure (orange line and symbol) and the simulations shown in Khalil et al. (2022) (symbols)

The model uses a stress-based liquefaction criterion, but the use of a different one may affect the results.

The main drawback of the proposed approach is still related to the lack of a correction factor for the fines content in the assessment of the DMT-based cyclic strength of soils. This issue will be addressed in future studies, based on field data from different test sites.

7 ACKNOWLEDGEMENTS

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8 REFERENCES

Aubry, D., Modaressi, A. 1996. GEFDYN, Manuel scientifique. Ecole Centrale Paris.

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

Chiaradonna, A., Flora, A., d'Onofrio, A., Bilotta, E. 2020. A pore water pressure model calibration based on in-situ test results. *Soils and Foundations* **60**(2), 327-341.

Chiaradonna, A., Monaco, P. 2022. Assessment of liquefaction triggering by seismic dilatometer tests: comparison between semi-empirical approach and non-linear dynamic analyses. *20th Int. Conf. of Soil Mech. and Geotechnical Engineering*, Sydney, 1-5 May 2022.

Chiaradonna, A., Ntritsos, N., Cubrinovski, M. 2022. CPT-based model calibration for effective stress analysis of layered soil deposits. *Proc. 5th International Symposium on Cone Penetration Testing*, Bologna, 876-882.

Chiaradonna, A., Tropeano, G., d’Onofrio, A., Silvestri, F. 2018. Development of a simplified model for pore water pressure build-up induced by cyclic loading. *Bulletin of Earthquake Engineering* 16(9), 3627–3652.

Chiaradonna, A., Tropeano, G., d’Onofrio, A., Silvestri, F. 2016. A simplified method for pore pressure buildup prediction: from laboratory cyclic tests to the 1D soil response analysis in effective stress conditions. *Procedia Eng.*, **158**: 302-307

Cubrinovski, M., Rhodes, A., Ntritsos, N., Van Ballegooy, S. 2019. System response of liquefiable deposits. *Soil Dynamics and Earthquake Engineering*, 124, 212-229.

Hujeux, J.-C. 1985. Une loi de comportement pour le chargement cyclique des sols. *Génie Parasismiq*, 287–302.

Jamiolkowski, M., Lo Presti, D. C. F., Manassero M. 2001. Evaluation of relative density and shear strength of sands from cone penetration test and flat dilatometer test. *Proc. Symp. on Soil Behaviour and Soft Ground Construction* GSP 119, 201–238. Reston, VA: ASCE.

Khalil, C., Regnier, J., Lopez-Caballero, F., Alves-Fernandes, V., Chiaradonna, A. et al. 2022. LICORNE a benchmark on numerical method for non-linear site response analysis involving pore water pressure. *Proc. 3rd European Conf. on Earth. Eng. & Seismology*, 3ECEES, Bucharest.

Ntritsos, N., Cubrinovski, M. 2020. A CPT-based effective stress analysis procedure for liquefaction assessment. *Soil Dynamics and Earthquake Engineering*,131,106063

Reyna, F., Chameau, J.L. 1991. Dilatometer Based Liquefaction Potential of Sites in the Imperial Valley. *Proc. 2nd Int. Conf. on Recent Advances in Geot. Earthquake Engrg. and Soil Dyn.,* St. Louis, May.

Tropeano, G., Chiaradonna, A., d’Onofrio, A., Silvestri, F., 2016. An innovative computer code for 1D seismic response analysis including shear strength of soils. *Géotechnique* **66**(2):95–105.

Tropeano, G., Chiaradonna, A., d’Onofrio, A., Silvestri, F. 2019. Numerical model for non-linear coupled analysis on seismic response of liquefiable soils. *Computers and Geotechnics* **105**, 211-227.