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A unified CPT–SPT correlation for non-crushable and crushable cohesionless soils

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SPT;
Compressibility;
Relative density

Abstract Despite the continuous developments in the Cone Penetration Test (CPT), the Standard Penetration Test (SPT) is still used extensively in site investigations. Hence, there is a constant need to update the CPT–SPT correlations to make use of the growing experience with the CPT. Many CPT–SPT correlations have been proposed based on case histories of predominantly quartzitic/non-crushable sands; yet, more efforts are needed to enhance their reliability. Additionally, recent studies were carried out on calcareous/crushable sands have shown that the common CPT–SPT correlations for these sands are even less reliable than they are for quartzitic sands. In this study, a proposed approach is presented to define the related soil compressibility parameters of the CPT–SPT correlations. The presented methodology enhances the reliability of the CPT–SPT correlations and provides a unified approach encompassing both crushable and non-crushable sands.

1. Introduction

Although there have been recent advances in the CPT and other contemporary in situ testing methods, the SPT continues to be a site investigation tool of choice in many parts of the world, because of its low cost and extensive past experience database. As such, there is a continuous need to develop reliable CPT–SPT correlations in order to make best use of the growing, more reliable CPT experience.

Many empirical correlations have been proposed to correlate the static cone tip resistance (q_c), to SPT N-value in siliceous soils. These correlations are often expressed as the ratio of (q_c/N), or equivalently as the dimensionless ratio ((q_c/p_a)/N). The CPT–SPT correlations are presented as a function of the fines content (*fines*%), the friction ratio (*FR*%), mean diameter (D_{50}) or the Soil Behavior Index (I_c) [1–8].

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Nomenclature

C_{age} correlation factor for sand aging in accordance with Kulhawy and Mayne [4]
C_n correction factor for the overburden pressure; $C_n = (p_a/\sigma'_v)^{0.5}$ (dimensionless)
CPT Cone Penetration Test
D_{50} mean soil grain diameter; the diameter at 50% passing in the gradation curve (mm)
D_r relative density = $(e_{max} - e)/(e_{max} - e_{min})$ (decimal number)
e void ratio = volume of voids/void of solids (dimensionless)
e_{max} maximum void ratio (dimensionless)
e_{min} minimum void ratio (dimensionless)
$f(I_c)$ regression function; $f(I_c) = 305\ Q_c$
fines% fines content; percentage of the soil with size less than 0.074 mm
F_r normalized friction ratio; $F_r = 100\ f_s/(q_c - \sigma)$ (dimensionless)
FR% friction ratio = $100\ f_s/q_c$ (percentage%)
f_s CPT sleeve friction (in kPa or bar)
I_c soil behavior index; $I_c = [(3.47 - \log Q_{tn})^2 + (1.22 + \log F_r)^2]^{0.5}$ (dimensionless)
ML Low Plastic Silt
N number of blows of SPT at 60% energy efficiency (dimensionless)
N_1 normalized SPT blows; $N_1 = N\ C_n$ (dimensionless)
$N_{1,c}$ normalized SPT blows considering soil compressibility (dimensionless)
OCR overconsolidation ratio (dimensionless)
p_a atmospheric pressure = 1 bar ≈ 100 kPa
q_c CPT tip resistance (in kPa or bar)
q_{c1} normalized CPT tip resistance (aka, q_{c1N}); $q_{c1} = (q_c/p_a)/(\sigma'_v/p_a)^{0.5}$ (dimensionless)
Q_t net CPT tip resistance ratio; $Q_t = (q_c - \sigma_v)/(\sigma'_v)$ (dimensionless)
Q_{tn} normalized net CPT tip resistance; $Q_{tn} = Q_t\ C_n$ (dimensionless)
$Q_{tn,c}$ normalized net CPT tip resistance considering soil compressibility (dimensionless)
SPT Standard Penetration Test
R^2 Coefficient of determination; $R^2 = 1$ – sum of the squares of the residuals of the correlation/sum of the square of the residuals around the average value
σ'_v effective vertical stress (in kPa)
σ total vertical stress (in kPa)
I behavior classification zone I: sensitive, fine grained soils
II behavior classification zone II: organic soils – clay
III behavior classification zone III: clay – silty clay to clay
IV behavior classification zone IV: silt mixtures – clayey silt to silty clay
V behavior classification zone V: sand mixtures – silty sand to sandy silt
VI behavior classification zone VI: sands – clean sand to silty sand
VII behavior classification zone VII: gravelly sand to dense sand
VIII behavior classification zone VIII: very stiff sand to clayey sand
IX behavior classification zone IX: very stiff fine – grained soils

1.1. Common CPT–SPT correlations

Some of the commonly accepted CPT–SPT correlations are presented by Eqs. (1)–(5) and Fig. 1:

1.1.1. Correlations with behavior index (I_c)

$$(q_c/p_a)/N = 8.5(1 - I_c/4.6) \quad (1)$$

(Lunne et al. [5])

$$(q_c/p_a)/N = 10^{(1.1268 - 0.2817 Ic)} \quad (2)$$

(Robertson [7])

1.1.2. Correlations with fines content (fines%)

$$(q_c/p_a)/N = 4.25 - (fines\%)/41.3 \quad (3)$$

(Kulhawy and Mayne [4])

$$(q_c/p_a)/N = 4.7 - (fines\%)/20 \quad (4)$$

(Chin et al. [2])

$$(q_c/p_a)/N = 5.44(D_{50})^{0.26} \quad (5)$$

(Kulhawy and Mayne [4])

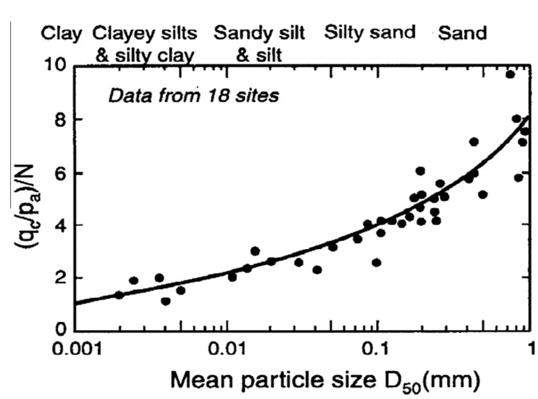

Figure 1 The CPT–SPT relationship as a function of D_{50} (Robertson et al. [1]).

1.1.3. Correlations with mean diameter (D_{50})

Comparing the CPT–SPT measurements in siliceous soils with the above common correlations, as presented later in this study, reveals that more efforts are still need to enhance the reliability of the CPT–SPT correlation in siliceous soils. Additionally, some studies showed that the common CPT–SPT correlations have poorer performance in calcareous soils than their performance in siliceous soils [9,10]. Akca [10] showed that the commonly applied CPT–SPT correlations give poor results in the calcareous soils. Elkateb and Ali [10] concluded that none of the existing correlations are applicable to calcareous sands. The performances of the common CPT–SPT correlations are investigated in calcareous soils. Similar conclusions to the work of Akca [9], and Elkateb and Ali [10] regarding the poor performance of the common CPT–SPT correlations are reached in the current study.

1.2. The need for unified CPT–SPT correlations

There is an existing need for unified and reliable CPT–SPT correlations, encompassing both calcareous and siliceous soils. This need arises from the necessity to achieve reliable and consistent geotechnical analyses (i.e., settlement and bearing capacity analyses for shallow and deep foundation) using SPT and/or CPT in both calcareous soils and siliceous soils.

Moreover, a reliable unified CPT–SPT correlation helps to avert specifying inconsistent SPT and CPT target values for the quality control in soil improvement projects. Such inconsistencies may result in unwarranted disputes between consultants and contractors especially if the soils to be improved have substantial variability in their crushability due to their variability in chemical composition, or due to the presence of both calcareous and siliceous soils with variable percentages.

There is also an increasing need for envisaging such correlations in liquefaction analyses. SPT has been used effectively in liquefaction triggering analyses since 1970s [11]. The currently available world-wide huge SPT databases for liquefaction triggering criteria in siliceous soils give impetus to continue using SPT as a standard test in liquefaction analyses [12]. Liquefaction analyses using CPT, provided reliable CPT liquefaction criteria are determined and adopted, would give nearly continuous profiles for the liquefaction susceptibility independent of the operator. These aspects would relieve much of concerns related to SPT that delivers discrete profiles having strong operator influence as well as substantial uncertainties regarding the energy efficiency in SPT tests [4].

Many studies tried to make use of the SPT database in liquefaction susceptibility to attain equivalent CPT liquefaction criteria by employing the common CPT–SPT correlations for siliceous soils (e.g., [13–16]). Nevertheless, the measured CPT data in liquefied siliceous soils after some recent earthquakes contradict with the common CPT liquefaction criteria that were inferred from the SPT liquefaction criteria combined with the common CPT–SPT correlations [17–19]. The observed constrictions shed some doubts regarding the common CPT–SPT correlations in siliceous soils.

Mejia and Yeung [20] investigated the liquefaction of calcareous soils during the 1993 Guam Earthquake; they concluded that the SPT criteria (formulated based on siliceous sands data) could also be used for calcareous sands. However, this observed equivalence of SPT data in both calcareous and siliceous soils contradicts with the observed low cone tip resistances in calcareous compared with siliceous soils under the same effective stress and for the relative densities [21–24].

Based on the above elaborations, a unified reliable CPT–SPT correlation, encompassing both crushable/calcareous soils and siliceous soils, may reduce the current uncertainties in liquefaction analysis in both calcareous and siliceous soils by reliably utilizing the abundant SPT liquefaction triggering database in siliceous soils.

In this study, a proposed approach is presented to enhance the reliability of the CPT–SPT correlations in both soils. This approach provides a unified methodology that encompasses both siliceous and calcareous soils through unified determination and quantification of the cohesionless soil compressibility.

2. Soil databases and performance of common correlations

2.1. Calcareous soil data

The analysis for crushable/calcareous soils utilized high quality CPT–SPT data (142 CPT–SPT data points) obtained from testing newly placed calcareous soil reclamations in the Arabian Gulf after improvement works [25]. The CPT tip resistance (q_c) and the sleeve resistance (f_s) were presented by averaging the test data within the same 30 cm of the SPT test. The percentage of carbonates, expressed as ($CaCO_3$), ranges between 63% and 93% (average of about 80%). The following geotechnical ranges characterize the database:

- The fines content (*fines*%) ranges between 3% and 25%.
- The mean diameter (D_{50}) ranges between 0.04 mm and 10 mm.
- The data are located within soil behavior zones (VI) through (VII) in the Soil Behavior Chart developed by Robertson [12] as shown in Fig. 2. Most of the data points lie in zones (VI) and (VII).
- Most of the data are for medium dense to very dense non-cohesive soils/sands as interfered from the CPT and SPT penetration tests.

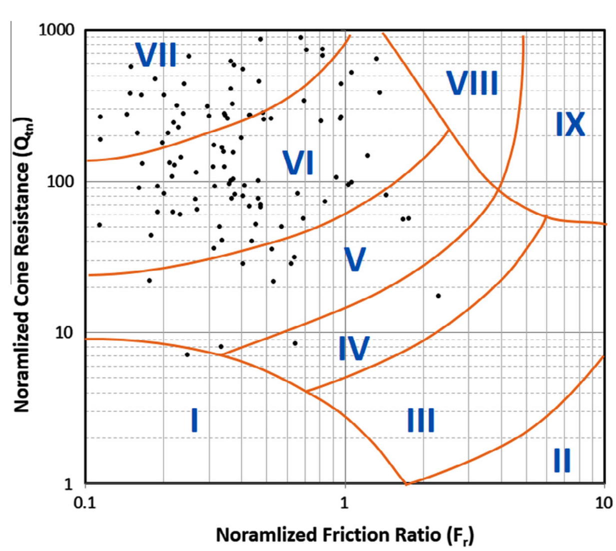

Figure 2 Classification of the calcareous soils.

- The presented data have a maximum Soil Behavior Index (I_c) value of about 2.6, indicating that the soil is draining according to Robertson and Cabal [8].

The normalized parameters used in the classifications and in the analyses (viz., Q_t, Q_{tn}, F_r and I_c) are as defined in accordance with Robertson [26], and Jefferies and Davies [27].

2.2. Siliceous soil data

The analysis for non-crushable/siliceous soils utilized CPT–SPT (294 CPT–SPT data points) obtained from two different case studies that were reported by Chin et al. [2] for a case study in Taiwan, and Ozan [28] for another case study in Turkey. Part of the data presented by Chin et al. [2] was for recent reclamation and the other part was for Holocene sands. All the data presented by Ozan [28] are for Holocene sands and silts. The following geotechnical ranges characterize the database:

- The fines content (*fines*%) ranges between 2% and 100%.
- The mean diameter (D_{50}) ranges between 0.004 mm and 7.9 mm.
- The data points lie within soil behavior zones (III–VII) in the Soil Behavior Chart presented by Robertson [26] as shown in Fig. 3.
- Most of the data are for loose to dense sands as interfered from the CPT and SPT penetration tests.
- The presented data have a maximum Soil Behavior Index (I_c), value of about 3.23.

It is to be noted that the siliceous soil database is generally finer than the calcareous soil database (as interfered from the *fines*% and I_c ranges above). Nevertheless, most of the data have an index value (I_c) less than 2.6 indicating that the soils are mostly draining. The data with (I_c) greater than 2.6 were mostly classified as Low Plastic Silt (ML) indicating the absence of plastic fines in the databases; this indicates that both siliceous and calcareous databases represent non-cohesive soils.

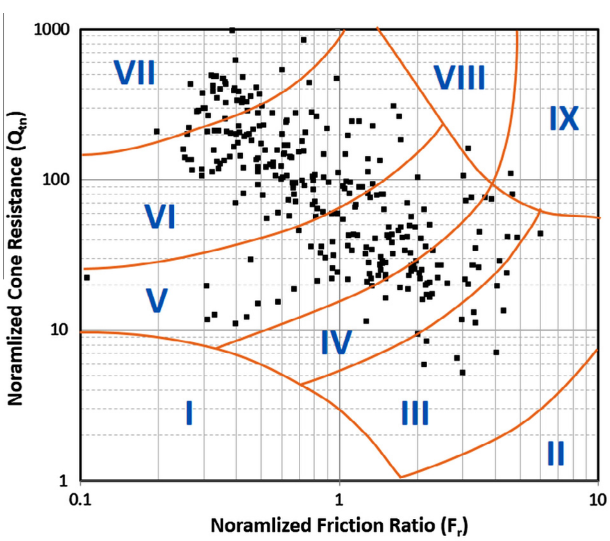

Figure 3 Classification of the siliceous soils.

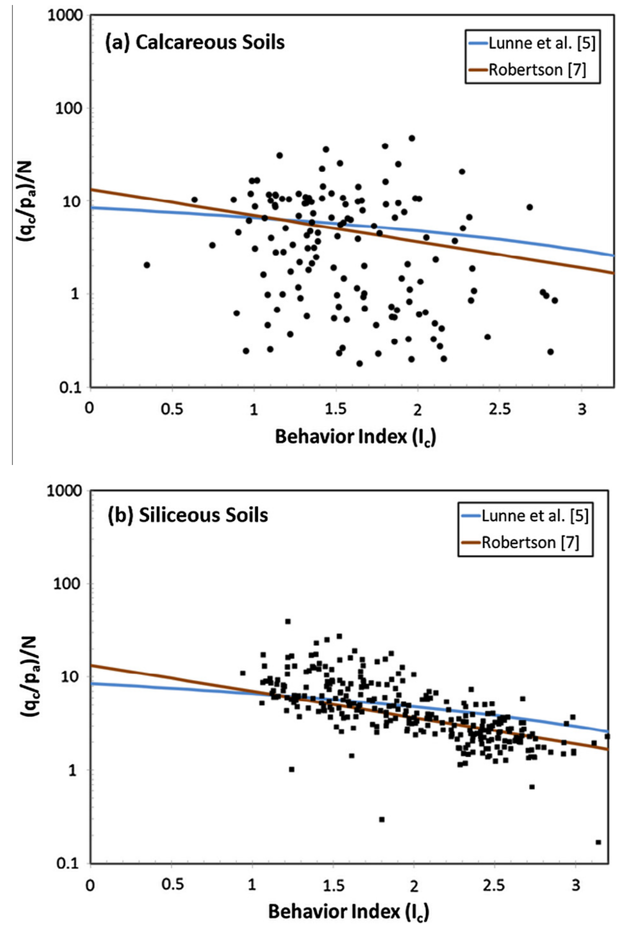

Figure 4 Performance of the common CPT–SPT relationships as a function of (I_c).

2.3. Performances of the common CPT–SPT correlations

The CPT–SPT measurements in siliceous and calcareous soils are compared with the common CPT–SPT correlations. The results of comparisons are shown in Figs. 4–6. Table 1 presents the coefficient of determination (R^2) for the different correlations for the siliceous and calcareous sands.

It is noted from Figs. 4–6 and Table 1 that the CPT–SPT correlations poorly simulate the q_c–N relationship in siliceous soil databases. The maximum coefficient of determination (R^2) has a maximum value of (0.221) for the correlation that was presented by Robertson [7], Eq. (2), using the behavior index (I_c). The rest of the correlations have lower coefficients of determination in siliceous soils.

It is also noted that Chin et al. [2] correlation, Eq. (4), gives negative value of the ratio ((q_c/p_a)/N) for (*fines*%) higher than 94%. Additionally, Chin et al. [2] correlation seems to be substantially deviated from the databases if (*fines*% > 40%) which indicate that this correlation should not be used for silts. The CPT–SPT correlation presented by Kulhawy and Mayne [4] adopting (*fines*%), Eq. (3), is close to Chin et al. [2] correlation in soils with low fines (*fines*% < 40%). Kulhawy and Mayne [4] correlation has relatively better performance than Chin et al. [2] correlation for (*fines*% > 40%).

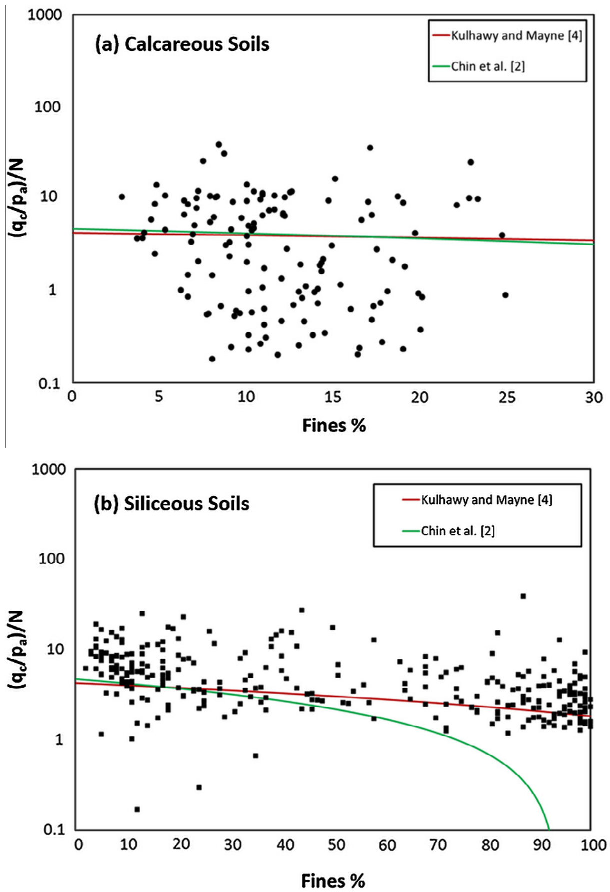

Figure 5 Performance of the common CPT–SPT relationships as a function of (*fines*%).

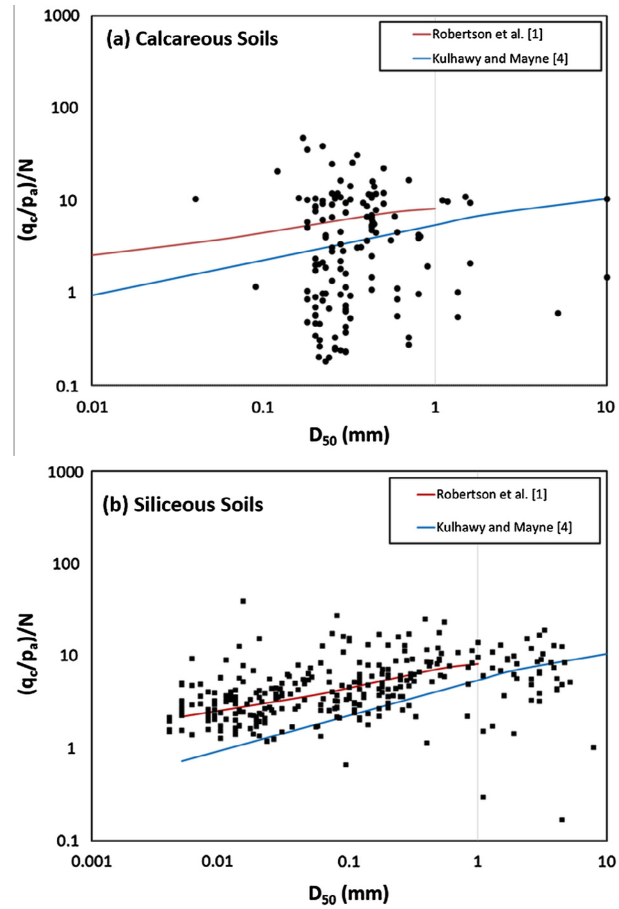

Figure 6 Performance of the CPT–SPT relationships as a function of (D_{50}).

The values of the coefficient of determination (R^2) that are presented in Table 1 for siliceous soils indicate that these common correlations are not much better than presenting the ratio ($(q_c/p_a)/N$) as an average value independent of the parameters that are assumed to control the CPT–SPT correlation.

The performance of the common correlation in calcareous soils is even poorer than their performance in siliceous soils. The maximum coefficient of determination (R^2) is only 0.096 for the correlation presented by Robertson [7]. The coefficient of determination is negative for the correlations based on the mean diameter (D_{50}) which indicate these correlations are less accurate than assuming an average value independent of the controlling parameter. The correlations based on the (*fines*%) have a determination factor (R^2) of almost zero indicating that they are not better than assuming an average value of ($(q_c/p_a)/N$) regardless of the controlling parameter (i.e., *fines*%).

The above discussion substantiates the needs for new enhanced CPT–SPT correlations that can accurately present the relationship between these two common penetration tests. Such reliable correlations are required for both crushable/calcareous and non-crushable/siliceous soils.

3. The proposed approach

In the following the proposed approach, is developed based on the equivalence of the relative density SPT and CPT correlations. This approach addresses the effect of soil compressibility on the penetration resistance and the selection of the representative soil compressibility factors. It is calibrated using the soil databases that were previously presented and utilized to verify the performance of the common CPT–SPT correlations.

3.1. Soil compressibility and the controlling factors of the CPT–SPT correlations

Schmertmann [29], Robertson and Campanella [30], and Kulhawy and Mayne [4] acknowledged that some cohesionless soils tend to have lower resistance than other soils even if both soils have the same relative density and they are tested under the same stresses. Soils that tend to have low tip resistances, such as calcareous soils, are known to have high compressibility; conversely, other soils with low compressibility, such as siliceous soils, tend to have high tip resistances.

The parameters anticipated to control the CPT–SPT correlations (viz., D_{50}, *fines*%, *FR*% and I_c) may be considered as an indications of the soil compressibility. Generally, compressibility is anticipated to increase with the increase in the fines content (*fines*%), the increase in the friction ratio (*FR*%), the decrease in the mean diameter (D_{50}) and the increase in behavior index (I_c). It is anticipated that the poor performance of the common correlation in calcareous soils, as illustrated from

Table 1 Coefficient of determination (R^2) for the common correlations.

Controlling parameter	Correlation; defining equation/figure	(R^2) for calcareous soils	(R^2) for siliceous soils
Behavior index (I_c)	Lunne et al. [5]; Eq. (1)	0.068	0.193
	Robertson [7]; Eq. (2)	0.096	0.221
Fines%	Kulhawy and Mayne [4]; Eq. (3)	0.002	0.076
	Chin et al. [2]; Eq. (4)	0.005	N/A[b]
Mean diameter (D_{50})	Robertson et al. [1]; Fig. 1	−0.026[a]	0.104
	Kulhawy and Mayne [4]; Eq. (5)	−0.029[a]	0.077

[a] The negative value for the coefficient (R^2) indicates that an average value would be more representative of $((q_c/p_a)/N)$ than the investigated correlation.
[b] Not available as Chin et al. [2] predicted negative values of $((q_c/p_a)/N)$ for (*fines*%) higher than 94%.

Figs. 4–6 and Table 1, results mainly from the lack of determination of the related compressibility factors that are to be adopted to define the compressibility of this crushable soils.

The common relationships between the CPT and CPT adopt one measure of the compressibility assuming that this parameter can be used to quantify the soil compressibility for both SPT and CPT. This approach may not be representative for crushable soils, which are known to have finer gradation after CPT and SPT probing. Bellotti et al. [31] demonstrated the effect of the CPT on the gradation of some crushable soils.

The crushability associated with SPT probing in calcareous soil is not similarly addressed so far; nevertheless, the samples extracted by SPT may be considered representative to the crushed gradation due to SPT probing. Conversely, SPT samples may not represent the gradation after the CPT probing due to the difference between the two probing methods (i.e., static CPT probing versus Dynamic SPT probing; solid cone probing in CPT versus open pipe probing in SPT). Thus, a need arises to adopt two parameters to describe the correlations between the CPT and SPT due to the anticipated difference in soil crushability/compressibility between the CPT and the SPT. This difference, in turn, causes subsequent differences in the CPT and SPT measurements.

While the mean diameter (D_{50}) (or alternatively *fines*%) obtained from the SPT samples in crushable/calcareous soils, can describe the soil compressibility related to SPT, these parameters cannot be used for the CPT since it does not represent the crushability/compressibility associated the CPT probing. It is anticipated that the material index (I_c) (or alternatively the *FR*%) may be considered more representative parameter of the soil compressibility affecting the CPT resistance. Agaiby et al. [25] concluded that adopting two compressibility parameters (i.e. D_{50} and I_c) enhances the CPT–SPT correlations in calcareous soils. Remarkably, Salehzadeh et al. [6] presented a similar trend in siliceous soils. They optimally adopted three parameters (viz., D_{50}, *FR*% and *fines*%) in addition to the excess pore water pressure associated with CPT probing to reach a coefficient of determination (R^2) of 0.597 in siliceous soils. Although Salehzadeh et al. [6] did not present the correlations in an equation form yet the improvement using multi-compressibility parameters in siliceous soils is much related to the current discussion.

Based on the above discussion, it is anticipated that employing two selected compressibility parameters may enhance the CPT–SPT correlations. This approach is justified by the difference between the two probing methods that generally affect the soil compressibility and hence the probing resistance.

In this study, an attempt is made to reach an enhanced and unified CPT–SPT correlation using two compressibility parameters (i.e., D_{50} and I_c) to define unified compressibility factors that can describe the compressibility of the siliceous as well as the calcareous soils. It is anticipated that the mean diameter (D_{50}) may represent the effect of the soil compressibility in SPT probing while the behavior index (I_c) may be considered as the compressibility parameter related to CPT probing.

3.2. Development of the proposed CPT–SPT correlation

Kulhawy and Mayne [4] presented expressions for the relative density of sands using both CPT and SPT as follows:

$$D_r^2 = (N \cdot C_n)/[(60 + 25 \log D_{50})OCR^{0.18}C_{age}] \quad (6)$$

$$D_r^2 = ((q_c/p_a) \cdot C_n)/(305Q_cOCR^{0.18}C_{age}) \quad (7)$$

where (Q_c) is a factor that expresses the compressibility of sands. Kulhawy and Mayne [4] empirically estimated this factor based on the results of calibration chambers for some clean sands as follows:

- $Qc = 0.91$ for highly compressible clean sands.
- $Qc = 1.0$ for medium clean compressible sands.
- $Qc = 1.09$ for low compressible clean sands.

To date, there is no quantitative estimate of (Q_c) factor without resorting to extensive calibration chamber tests. In this study, an assessment of this factor is determined utilizing the calcareous and siliceous databases.

From Eqs. (6) and (7), the following correlations between CPT and SPT can be deduced as follows:

$$(q_{c1}/p_a)/[N_1/(60+25\log D_{50})] = (q_c/p_a)/[N/(60+25\log D_{50})] = 305Q_c \quad (8)$$

Thus, for the sands with a (D_{50}) range that is between 0.1 and 1.0 mm, the ratio ($(q_c/p_a)/N$) for medium compressible sands is expected to be between 5.5 and 8.3. These values are in line with some reported typical values for sands (e.g., 5–6 for sand and 8–10 for gravel by Schmertmann [29]; 5.7 by Danziger et al. [32]; and 7.7 by Akca [9]).

It is to be noted that the main uncertainty in Eq. (8) is the compressibility factor associated with the CPT testing (Q_c). In order to have a representative unified CPT–SPT correlation, this factor has to be quantified. Agaiby et al. [25] presented CPT–SPT correlations for recently deposited calcareous soils by replacing the term (q_{c1}) by (Q_{tn}) as follows:

$$Q_{tn}/[N_1/(60+25\log D_{50})] = Q_t/[N/(60+25\log D_{50})] = f(I_c) \quad (9)$$

where the function $f(I_c)$ is a function that is to be determined by regression analysis using soil databases.

The regression function ($f(I_c)$) in Eq. (9) depends on the behavior index (I_c) based on the assumption that soil compressibility associated with CPT can be described as a function of the Soil Behavior Index. This is in line with the previous discussions of the related soil compressibility factors. Additionally, the regression function ($f(I_c)$) is expected to be an exponential function based on the observed relative better performance of the correlation of Robertson [7] (Eq. (2)) compared with the other common CPT–SPT correlation.

Based on Eqs. (8) and (9), the soil compressibility (Q_c) can be defined as follows:

$$Q_c = (Q_{tn}/[N_1/(60+25\log D_{50})])/305 = f(I_c)/305 \quad (10)$$

Using the presented databases, regression analyses were carried out for on the databases to quantify the regression function ($f(I_c)$) and hence the soil compressibility (Q_c) with the range if draining soils, i.e., with ($I_c < 2.6$).

3.3. Quantification of the compressibility factor (Q_c) for calcareous soils

The regression analyses carried out on the calcareous soils for ($f(I_c)$) are presented by the below equation:

$$(f(I_c))_{\text{Calcareous}} = 7524.1\exp(-1.784I_c) \quad (11)$$

Fig. 7 shows the regression analysis for calcareous soils, Eq. (11), plotted with the data of both calcareous and siliceous soils. It is noted from Fig. 7 that the abovementioned correlation for calcareous soils also matches with the trend of the siliceous soils. As shown later in this study, a unified form of the presented correlation may present via a regression analysis for the data of both soil types; this unified regression is shown in Fig. 8.

The relationship presented by Eq. (11) has a coefficient of determination (R^2) of 0.614 (based on 142 data points). It is to be noted that the coefficient of determination (R^2) in the above analyses is much higher than the coefficients of determinations in listed in Table 1 for calcareous soils. The improved performance indicates the suitability of the selected compressibility factors attempted in this study. Based on that, the soil compressibility factor (Q_c) for calcareous soils can be described as below:

$$(Q_c)_{\text{Calcareous}} = 24.67\exp(-1.784I_c) \quad (12)$$

3.4. Quantification of the compressibility factor (Q_c) for siliceous soils

The same approach above is also attempted in siliceous soils. The regression function ($f(I_c)$) is presented by Eq. (13) with a coefficient of determination (R^2) of 0.566 (based on 294 data points):

$$(f(I_c))_{\text{Siliceous}} = 15502\exp(-2.291I_c) \quad (13)$$

Fig. 7 shows the proposed correlation for siliceous soils, Eq. (13), plotted with the data of both calcareous and siliceous soils. It is noted that the correlation presented for siliceous soils in Eq. (13) also matches with the trend of the calcareous soils. A unified form is presented for both types of soils in Fig. 8 as elaborated later in this study.

The coefficient of determination (R^2) of the relationship presented by Eq. (13) is slightly less than the coefficient of determination of the calcareous soil; yet, it is higher than the coefficient of determination of the common correlations listed in Table 1. Eq. (13) also implies that the compressibility factor (Q_c) for siliceous soils can be expressed as:

$$(Q_c)_{\text{Siliceous}} = 50.83\exp(-2.291I_c) \quad (14)$$

3.5. Unified quantification of the compressibility factor (Q_c)

The correlations for calcareous and siliceous soils are plotted together in Fig. 7 in order to check if the expressions of the regression functions ($f(I_c)$) (or alternatively the expressions of Q_c) can be unified to represent a unified quantification of the compressibility associated with CPT probing. It is noted from Fig. 7 that the differences between the two separate correlations for the calcareous and siliceous soils are small for the range of the presented data. This implies that both sets can be described by a uniform compressibility factor (Q_c) without jeopardizing the accuracy within the presented range.

The above conclusion is expected since the main difference between the calcareous soils and the siliceous soils is the difference in the compressibility. Hence, once a unified account of the soil compressibility is reached, a unified CPT–SPT correlation encompassing both siliceous and calcareous soils can subsequently be reached.

A unified correlation for both siliceous and calcareous databases is attempted. The results of the unified regression analysis are shown in Eq. (19) and in Fig. 8.

$$f(I_c) = 14115\exp(-2.248I_c) \quad (15)$$

The compressibility factor (Q_c) for the both siliceous and calcareous soils is described by the below equation:

$$Q_c = 46.28\exp(-2.248I_c) \approx 46.3\exp(-2.25I_c) \quad (16)$$

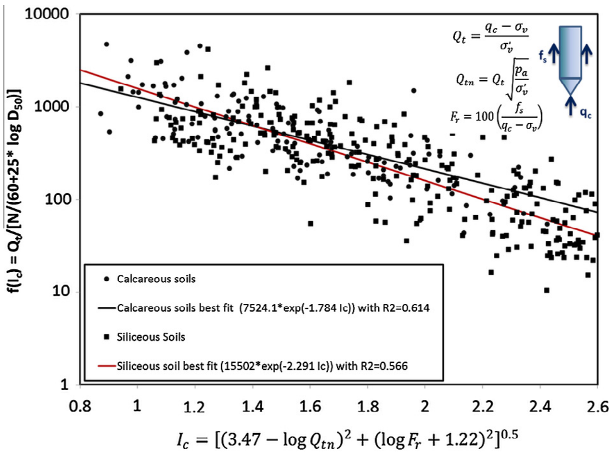

Figure 7 CPT–SPT correlations for calcareous and siliceous soils as two distinct correlations.

The above analysis shows a unified CPT–SPT relationship for both calcareous and siliceous soils with a slightly better coefficient of determination (R^2) of 0.634 (based on 436 data points) than the two distinct CPT–SPT correlations.

The slight improvement in the coefficient of determination, in the unified analysis, indicates the both calcareous and siliceous databases complement each other. This unified trend is also graphically demonstrated in Figs. 7 and 8. It also implies that the unified expression of (Q_c), Eq. (16), represents a general expression that quantify the compressibility associated with CPT testing irrespective of the soil geological origin.

Comparing the obtained coefficient of determination (R^2) for the unified correlation with the latest works pertaining to the CPT–SPT relationships for non-calcareous soils (e.g., Kara and Gündüz [33], Salehzadeh et al. [6]), it can be concluded that different models with different controlling factors of the CPT–SPT correlations generally do not have correlation coefficients (R^2) much greater than 0.6. As such, the presented unified correlation may be considered as representative general form for soils with different geological conditions.

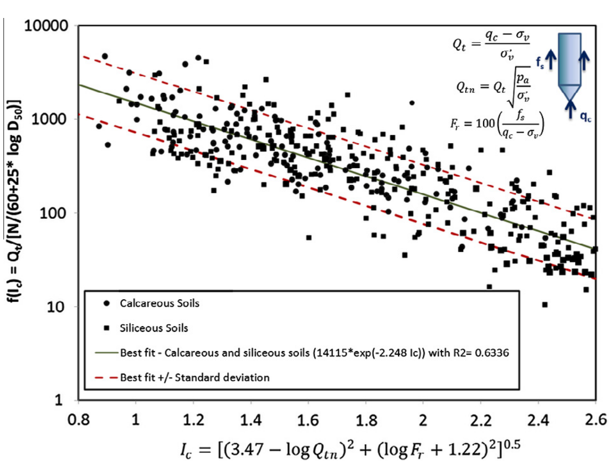

Figure 8 Unified CPT–SPT correlations for both calcareous and siliceous soils.

3.6. Unified CPT–SPT correlation

The unified CPT–SPT correlation is given by substituting the compressibility parameters (Q_c), defined in Eq. (16), into Eq. (10). It is described by the below equation:

$$Q_{tn}/N_1 = 14115\exp(-2.25I_c)/(60 + 25\log D_{50}) \quad (17)$$

The above correlation represents the relationship between the CPT and the SPT different soils with different geological origins. This unified form is based on having two compressibility parameters: (D_{50}) for SPT and (I_c) for CPT. The function form of both parameters (i.e., the function of D_{50} and the exponential function for I_c) is considered suitable forms based on the previous discussions and the presented regression analyses.

The parameters in Eq. (17) are obtained from different tests (i.e., Q_{tn} and I_c from CPT; N and D_{50} from SPT and gradation tests on the SPT samples). As such, the unified correlation is better to be rewritten by relocating the parameters of CPT in one side of the relationship, and the parameters related to SPT to the other side. A more appropriate form of the unified correlation may be presented as follows:

$$Q_{tn,c} = 5.08\ N_{1,c} \quad (18)$$

where ($Q_{tn,c}$) represents the CPT to resistance normalized to 1 bar overburden pressure as well as the effect of soil compressibility; it is given as follows:

$$Q_{tn,c} = Q_{tn,c}/Q_c = Q_{tn,c}/[46.3\exp(-2.25I_c)] \quad (19)$$

($N_{1,c}$) represents the SPT number of blows at 60% energy efficiency normalized to 1 bar overburden pressure as well as the effect of soil compressibility; it is given as follows:

$$N_{1,c} = N_1/(1 + 0.42\ log D_{50}) \quad (20)$$

The unified correlation, presented by Eqs. (18)–(20), allows to separate the CPT and SPT measurements and compressibility measures. Hence, the transformation from one test (e.g., CPT) to the other test (e.g., SPT) can be straightforwardly performed. It is also to noted that the consistency of the penetration resistances normalized for compressibility (viz., $Q_{tn,c}$ and $N_{1,c}$) stems from being both related to the relative density. It is foreseen that the proposed normalization for the compressibility will allow the SPT databases to be simply transformed into equivalent CPT databases, which may enhance the CPT correlations related to the foundation and liquefaction analyses.

4. Applicability, advantages and disadvantages of the proposed unified correlation

As presented above, the proposed approach is based on quantification of the compressibility factor related to CPT (i.e., Q_c) in terms of the behavior index (I_c) and adopting the mean diameter (D_{50}) as the compressibility factor for SPT. Conversely, the previous common approaches adopt a single compressibility parameter (i.e., D_{50}, *fines*%, *FR*% or I_c) to describe the CPT–SPT relationship. A database of non-cohesive soils having different locations (Arabian Gulf, Taiwan, and Turkey), different geological origins (calcareous, and siliceous), and different aging conditions (recent reclamations, and Holocene formations), was utilized to test the previous common CPT–SPT correlation and to develop and calibrate the proposed relationship. The utilized soil databases comprising calcareous and siliceous soils cover a wide range of compressibility as siliceous non-cohesive soils are considered of low to medium compressibility while calcareous non-cohesive soils are considered of high compressibility due to the difference in the geological origin of the two soils (Schmertmann [29]; Robertson and Campanella [30]; Kulhawy and Mayne [4]).

The proposed approach was found to provide more representable CPT–SPT relationship than the common correlation. The coefficient of determination (R^2) was found to be 0.634 compared with much lower values of the coefficient of determination for the previous correlation (viz., −0.029 to 0.221). It is believed that the lower coefficient of determinations for the common correlation, as revealed by the analyses, is due to the incomplete incorporation of the soil compressibility, particularly for CPT. The adopted approach of employing two compressibility parameters adopted in the proposed correlation enhanced the inclusion of the compressibility effects into the CPT–SPT relationship.

The coefficient of determination (R^2) for the unified analysis is higher than the coefficient of determinations of the analysis for each of the soil types. This note may imply that both databases (siliceous and calcareous) complement each other. It may ensure that the proposed unified approach can generally be considered as representative for cohesionless soils within the range of the analysis (i.e., $I_c < 2.6$). The generality of the proposed correlation is the anticipated based on adequate quantification of the soil compressibility factor associated with CPT-relative density relationship (Q_c) and the inclusion of compressibility factor related to the standard penetration test in terms of the mean diameter (D_{50}).

Moreover and to ensure the validity of the proposed correlation, it is tested using micaceous sands. This sand type was not included among the databases utilized in developing the proposed approach. Micaceous sands (siliceous sands with mica plates) are known to have higher compressibility than normal siliceous cohesionless sands that does not contain mica even if the parentage of mica is small [34,4,35]. The CPT–SPT data of the case study of medium dense micaceous sands (mica% = 10%), which was presented by Robertson [36] at McDonalds Farm site, are plotted versus the proposed correlation in Fig. 9. A good agreement was observed between the proposed unified correlation and the reported data despite the fact that micaceous sands were not included among the databases used in developing the unified correlation.

The observed good performance of the proposed correlation for a soil type that was not included as well as the obtained high coefficient of determination, compared with the common correlations, ensures that the proposed correlation can be considered as representative of cohesionless soils irrespective of its origin. Additionally, as the databases cover wide range of reclaimed and aged sands, it is anticipated that the proposed correlation performs well and considered applicable over the wide range of cohesionless soils.

The main disadvantage of the proposed correlation is it needs more parameters than the previous correlations. Yet, it is suggested to use the form of the correlation presented by Eqs. (18)–(20), since it collects the data of SPT in one side of the equation and the data related to CPT in the other side. In this regard, it is suggested to consider utilizing the compressibility normalized penetrations ($Q_{tn,c}$) and ($N_{1,c}$) in lieu of (Q_{tn}) and ($N_{1,c}$) in CPT and SPT correlations. It is also foreseen that further enhancement could be obtained in the proposed CPT–SPT correlation by calibrating the proposed expression of the CPT compressibility factor (Q_c) using calibration chambers to identify the effect of the lateral stress and the relative density on the soil compressibility.

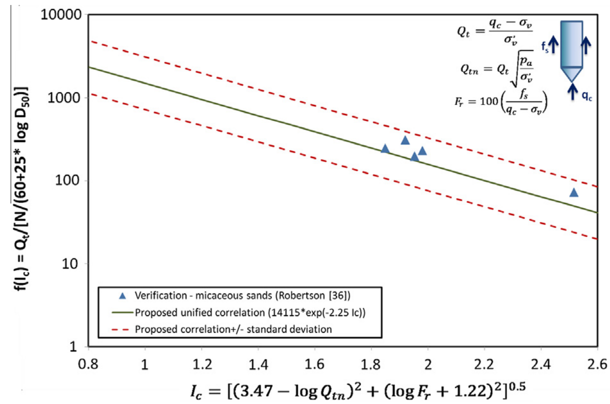

Figure 9 Micaceous soil data versus the proposed unified CPT–SPT correlation.

5. Conclusions and recommendations

In this study, a proposed unified approach, correlating CPT and SPT readings for both crushable/calcareous and non-crushable/siliceous sands, is presented. The presented approach incorporates quantifying the soil compressibility related to CPT in terms of the behavior index (I_c), and the compressibility related to SPT in terms of the mean diameter (D_{50}).

The correlation is calibrated using data encompassing both siliceous and calcareous soils. A proposed normalization for soil compressibility is also presented along with the unified correlation, which allows straightforward conversion between SPT and CPT data regardless of the geological origin of the considered sands. The proposed unified correlation shows an enhanced representation of CPT–SPT correlation for the presented siliceous and calcareous sands databases. Additionally, a case study of CPT–SPT data in micaceous sands was analyzed and found to be in good agreement of the proposed unified correlation.

The presented methodology potentiates the reliability of the CPT–SPT correlations in cohesionless soils by introducing a unified expression of the soil compressibility affecting the CPT and SPT measurements. The presented correlation may be benefited in envisaging CPT analyses and correlations for foundations and assessing liquefaction susceptibility for both siliceous and calcareous soils.

More research addressing the effect of the cohesionless soil compressibility is recommended to further enhance the presented approach. In this regard, the use of calibration chamber to calibrate the proposed soil compressibility relationship, and to determine the effect of the lateral stresses and the relative density, is recommended.

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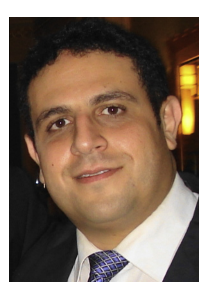

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