CPT-SPT correlations for calcareous sand in the Persian Gulf area

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ABSTRACT: The main objective of this study is to examine the applicability of various CPT-SPT correlations available in the geotechnical literature to relatively young calcareous sand in the Persian Gulf area. These correlations were compared with high quality CPT and SPT data collected from various projects in the UAE area. The study results indicated that almost all of the existing correlations are not applicable to the fine to medium grained sand in the UAE and that the ratio between normalized cone tip resistance and SPT blow counts is relatively higher than the typical values in the geotechnical literature. The study results were used to develop region-specific CPT-SPT correlations for the calcareous sand in the UAE. Statistical analyses were also performed to quantify the uncertainty in these correlations and to develop risk-based CPT-SPT correlations.

1 INTRODUCTION

The Standard Penetration Test (SPT) is the most commonly used field test to determine the engineering properties of granular materials. This can be attributed to its simplicity and cost-effectiveness in addition to the presence of several well-established SPT-based design techniques for various engineering applications in the geotechnical literature. On the other hand, the Cone Penetration Test (CPT) has been regarded as a more reliable alternative to the SPT due to its reliability, repeatability, and standardization, especially after the introduction of the electric CPT in the 1940s.

Several correlations have been developed in the geotechnical literature to correlate CPT results to SPT blow counts (N), as presented in the following sections. The main objective was to use CPT data in the well established SPT-based design approaches, or alternatively convert SPT blow counts into CPT tip resistance in cases where the CPT-based geotechnical correlations are more reliable. To the authors' knowledge, most, if not all, of the existing correlations were limited to uncemented silica sands. Calcareous sand is commonly found in tropical and subtropical coastal areas, such as the Persian Gulf area. This sand is typically characterized by high void ratio, high grain crushability, brittle behavior, and higher compressibility compared to silica sand and hence could behave differently especially with increased carbonate contents.

Therefore, there is a need to extend the existing CPT-SPT correlations to calcareous sand; especially with the launch of several mega scale projects in the Persian Gulf area that involve reclamation works using calcareous sand.

The main objective of this study is to examine the applicability of various CPT-SPT correlations to relatively young calcareous sand in the Persian Gulf area. This was carried by comparing these correlations with high quality CPT and SPT data collected from various projects in Dubai, Abu Dhabi, and Sharjah in the United Arab Emirates (UAE). In addition, statistical techniques were used to quantify the uncertainty in these correlations and to develop region-specific risk-based CPT-SPT correlations for calcareous sand.

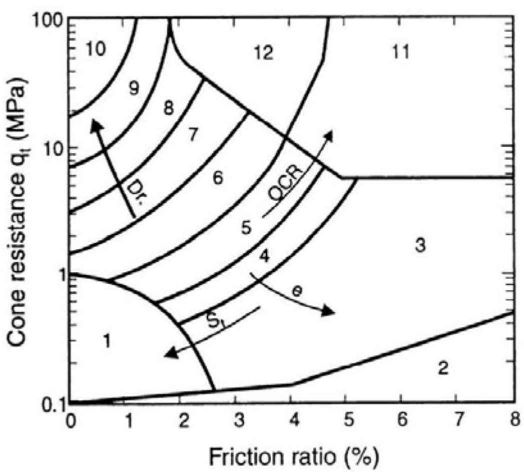
2 BACKGROUND ON THE CPT-SPT CORRELATIONS

Several empirical correlations between CPT and SPT results have been developed in the geotechnical literature. These correlations were mainly developed through regression analyses to CPT and SPT data collected in Europe and North America. This started in the early 1980s with the early work of Douglas and Olsen (1981). Robertson et al. (1983) carried out an extensive review of CPT –SPT correlations available at that time and used data from field testing in the province of British Columbia in Canada to develop CPT-SPT correlation for SPT data corrected to 60% energy ratio (N_{60}). The published correlation was digitized in the current study and regression analyses were carried out to develop a mathematical form suitable for use with standard computer spread sheets. This mathematical form was in the form:

$$(q_c/P_a)/N_{60} = 7.735\ (D_{50})^{0.28} \qquad (1)$$

Where: q_c is the CPT tip resistance; P_a is the atmospheric pressure; and D_{50} is the soil median size in mm.

Robertson et al. (1986) proposed a CPT-SPT correlation where the ratio between normalized cone tip resistance (q_c/P_a) and N_{60} was given for different soil types determined from their soil behavior type classification chart, as shown in Figure 1.



Zone	Soil Behavior Type	$\frac{(q_c/p_a)}{N_{60}}$
1	sensitive fine grained	2
2	organic soils - peats	1
3	clay	1
4	silty clay to clay	1.5
5	clayey silt to silty clay	2
6	sandy silt to clayey silt	2.5
7	silty sand to sandy silt	3
8	sand to silty sand	4
9	sand	5
10	dense sand to gravelly sand	6
11	very stiff fine grained	1

Figure 1. Ratio of normalized cone tip resistance and N_{60} for different soil behavior types (modified from Robertson et al. 1986)

Kulhawy and Mayne (1990) extended the Robertson et al. (1983) correlation based on additional data that became available to them in the late 1980s and developed a mathematical expression for their updated SPT-CPT correlation. It should be noted that the SPT data used to develop this correlation was not corrected for the different energy ratios used in the field. In the current study, a correction factor was added to the original mathematical expression of Kulhawy and Mayne (1990) so that it becomes applicable to SPT blow counts corrected to 60% energy ratio (N_{60}). This correction factor was determined assuming that most of the data used in developing the original expression had an energy ratio of about 50%. This resulted in the following revised expression:

$$(q_c/P_a)/N_{60} = 6.53\,(D_{50})^{0.26} \tag{2}$$

Kulhawy and Mayne (1990) also developed a correlation between the ratio between normalized cone tip resistance and uncorrected SPT blow counts, and fine content (FC). This correlation was expressed in the form:

$$(q_c/P_a)/N = 4.25 - FC/41.3 \tag{3}$$

Lunne et al. (1997) upgraded the CPT-SPT correlation developed by Robertson et al. (1986) to overcome the discontinuity in the correlation when moving from one Soil Behavior Type to another. They developed a mathematical continuous expression using a modified version of the Soil Behavior Type Index (I_c) of Jefferies and Davies (1993) in the form:

$$(q_c/P_a)/N_{60} = 8.5\,(1-I_c/4.6) \tag{4}$$

3 APPLICABILITY OF THE EXISTING CORRELATIONS TO THE PERSIAN GULF CARBONATE SANDS

The applicability of the existing CPT-SPT correlations to calcareous sands in the Persian Gulf area was examined this study. This involved collecting high quality adjacent CPT and SPT data from five sites in the United Arab Emirates (UAE): three sites in Dubai, one site in Abu Dhabi and one site in Sharjah. The data collected were mostly from uncompacted reclamation sand fills, with thickness ranging from 8 to 12 m, obtained from dredging operations off the coast of the UAE. Little data was collected from the surficial native calcareous sand commonly found along the coastal areas of the UAE. Both the sand fill and the native sand had relatively similar characteristics. They were fine to medium grained, with fines and carbonate contents ranging from 5 to 20% and 50 to 75%, respectively, and with variable amounts of sand to gravel sized shells.

The applicability of the D_{50}-based correlations of Robertson et al. (1983) and Kulhawy and Mayne (1990) to the collected data is shown in Figure 2. A considerable scatter of the collected data can be noticed relative to the two correlations. In addition, no general trend was noted in the collected data with the change in D_{50} indicating poor applicability of these correlations to the UAE calcareous sand. In a similar fashion, the fines content-based correlation of Kulhawy and Mayne (1990) showed a poor fit to the collected data, as shown in Figure 3.

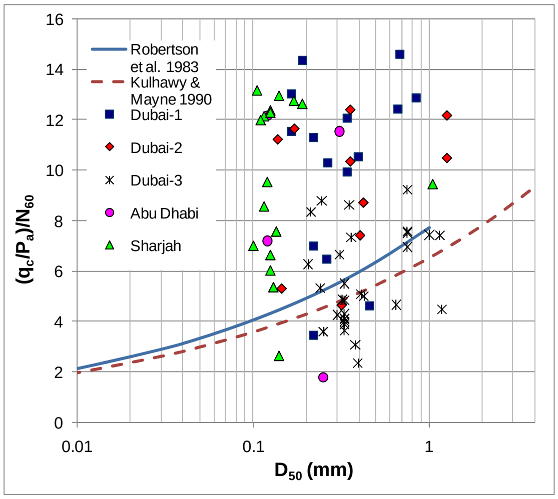


Figure 2. Applicability of the D_{50}-based correlations of Robertson et al. (1983) and Kulhawy and Mayne (1990) to the UAE calcareous sand.

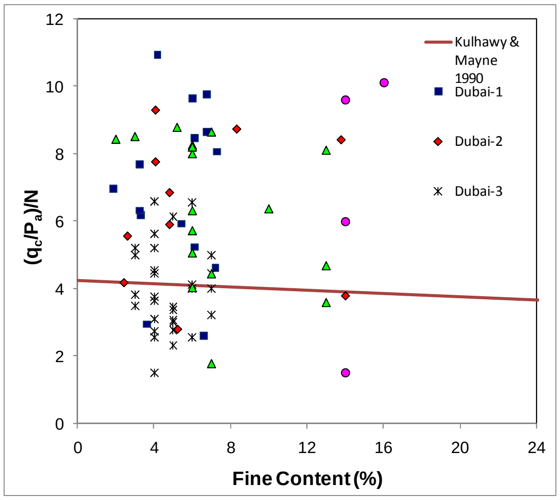


Figure 3. Applicability of the fine content - based correlation of Kulhawy and Mayne (1990) to the UAE calcareous sand.

The poor applicability of the existing correlations could be attributed to any of the following:

- The distinct engineering characteristics of calcareous sand, such as high compressibility and crushability, compared to siliceous sand for which most of the existing correlations were developed.
- The reliance on a single parameter of the grain size distribution, such as D_{50} or fines content, which may not be solely sufficient to develop a reliable CPT-SPT.
- The variable amounts of shells encountered in the sand fill, which could have influenced the CPT and SPT results.
- The absence of SPT energy measurements in the collected data.

The applicability of the existing I_c-based correlation of Lunne et al. (1997) to the collected data is shown in Figure 4. As the case for the two previous correlations, considerable scatter was noticed in the collected data. The overall trend of the data, however, was in reasonable agreement with that of the existing correlation. This can be attributed to the fact that I_c is calculated from measured quantities, such as CPT tip resistance, that could have been affected by the engineering characteristics of soil rather than being an index parameter. Figure 4 shows that the linear trend line of the collected data, as determined from regression analyses, is almost parallel to that of the existing correlation. The I_c-based correlation should be used with caution, however, due to the wide scatter in the data, which resulted in several data points located outside typical design ranges. Example of these ranges is the Euro Code 7.0 design range where the characteristic soil parameter is taken equal to the mean ± one half the standard deviation. The Euro Code 7 range is shown in Figure 4 and was obtained from statistical analysis of the collected data, as explained in Section 4.

It can be also concluded from Figure 4 that the ratio $(q_c/P_a)/N_{60}$ for calcareous sand is relatively higher than that of siliceous sand. This could also indicate that the presence of shells in calcareous sands might have a bigger influence on the CPT tip resistance value compared to the SPT blow counts.

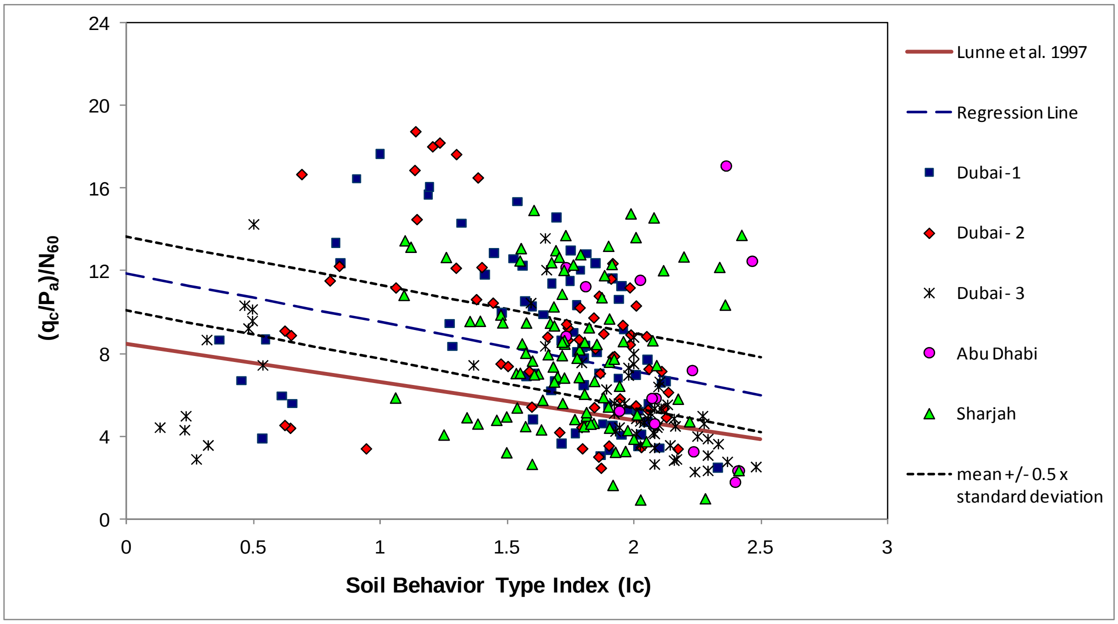


Figure 4. Applicability of the I_c-based correlations of Lunne et al. (1997) to the UAE calcareous sand.

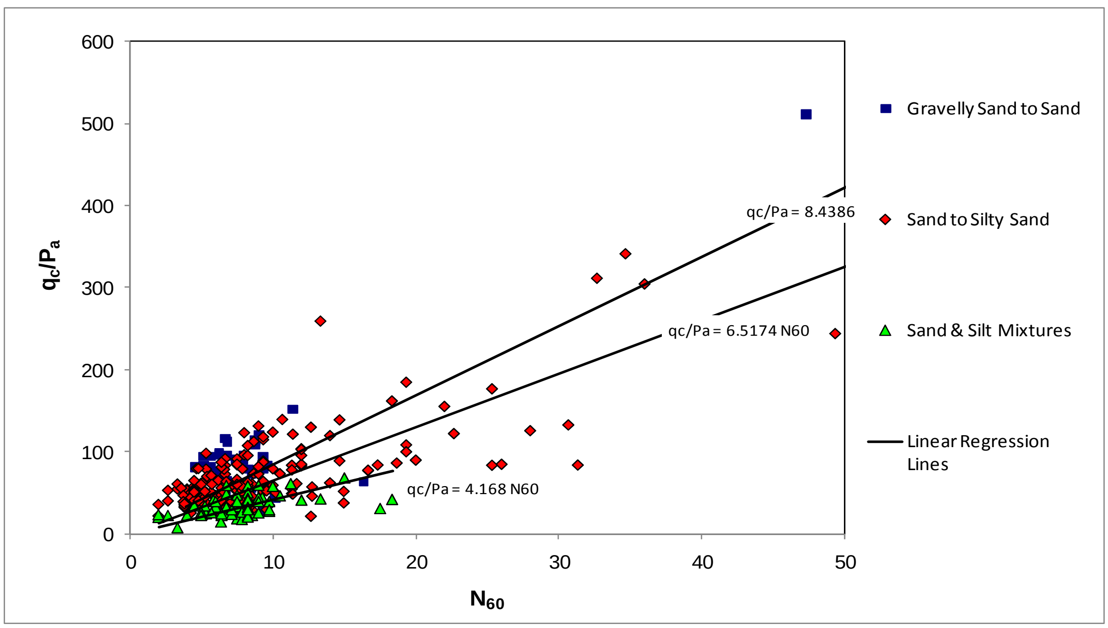


Figure 5. Applicability of the Robertson et al. (1986) correlation to the UAE calcareous sand.

The applicability of the Robertson et al. (1986) correlation, presented in Figure 1, to the collected data is shown in Figure 5. For the sake of comparison, the collected data was expressed in the form:

$$q_c/P_a = C \,.\; N_{60} \qquad (5)$$

where C is a proportionality constant.

The value of the proportionality constant (C), as determined from regression analyses, for the gravely sand to sand, sand to silty sand, and sand and silt mixtures was found equal to 8.44, 6.52, and 4.17, respectively. These values are 1.4 to 1.44 times the values recommended by Robertson et al. (1986). This supports the above conclusion that the ratio $(q_c/P_a)/N_{60}$ for calcareous sand is relatively higher than that of siliceous sand.

4 REGION SPECIFIC CPT-SPT CORRELATIONS

The results presented in the previous section indicate that some modifications are needed to the existing CPT-SPT correlations to best fit the calcareous sands data collected from the UAE. The scatter in the grain size-based correlations was considered too wide and difficult to improve by simple regression procedure. Hence, no attempt was made in this study to develop region-specific CPT-SPT correlations based solely on grain size characteristics.

The I_c-based correlation of Lunne et al. (1997) was considered amenable to modification since the overall trend of the collected data was relatively similar to the existing correlations, as discussed in Section 3. The proposed modification involved the introduction of the regression line equation, as shown in Figure 4, as a replacement to the Lunne et al. (1999) correlation (Equation 4), where the relationship between CPT tip resistance and SPT blow counts can be expressed as:

$$(q_c/P_a)/N_{60} = 11.88\ (1-I_c/5) \qquad (6)$$

A correction factor R was added to Equation 6 to quantify the influence of the significant scatter in the collected data around the best-fit (regression) line resulting in the following expression:

$$(q_c/P_a)/N_{60} = 11.88\ (1-I_c/5) + R \qquad (7)$$

The correction factor R can be regarded as the difference between the field values of the ratio $(q_c/P_a)/N_{60}$ and the values of this ratio determined using Equation 6. Since the value of R varies from one field data to another, statistical analyses were carried out where R was treated as a stationary random variable. In these analyses, histogram of the random variable R was generated and used to develop a relationship between the R and the target probability that the actual/field value of $(q_c/P_a)/N_{60}$ will exceed the value calculated using Equation 7. This is shown in Figure 6, which can be used in risk-based assessment of the CPT-SPT correlation. For example, if it is required to determine q_c from SPT data with a target probability that no more than 10% of the actual/field value of q_c would be smaller than the predicted one, a probability of exceedence of 90% should be used in Figure 6. This will result in an estimate of R equal to -4.0 which will decrease the value of $(q_c/P_a)/N_{60}$ calculated using Equation 6.

For the Robertson et al. (1986) correlation, it was proposed that the tabulated values of the ratio between q_c/P_a and N_{60} could be replaced by the proportionality constant (C) of Equation 5. As explained earlier, this will result in higher ratios of $(q_c/P_a)/N_{60}$ compared to those shown in Figure 1. To quantify the effect of the scatter in field data, statistical analyses were carried out assuming the constant C to be a random variable. Similar to the case for the factor R, histograms of the constant C for the three soil types considered in this study. These histograms were used to produce relationships between C and the target probability that the actual (field) value will exceed the one calculated using Equation 5, as shown in Figure 7. This figure can also be used in risk-based estimate of the ratio $(q_c/P_a)/N_{60}$ in a way similar to that used with the factor R. For example, to determine q_c from SPT data in sandy to silty sand soil with a target probability that no more than 10% of the actual/field value of q_c would be smaller than the predicted one, a probability of exceedence of 90% should be used with the relevant curve in Figure 7. This will result in an estimate of C equal to 4.23 compared to the 6.52 value obtained from deterministic regression analysis.

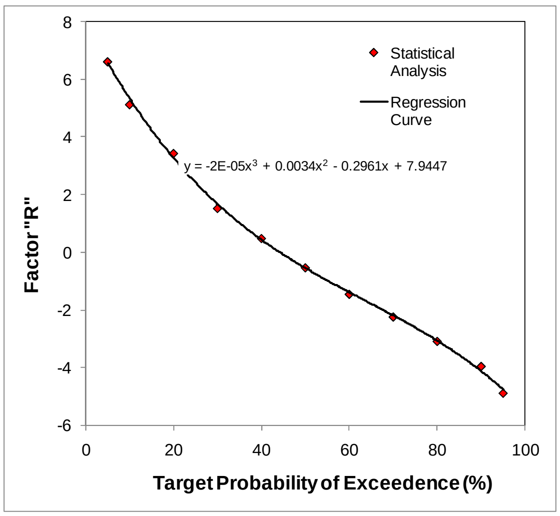


Figure 6. Variation of the factor (R) with the probability of that field data will exceed the values predicted using Equation 6.

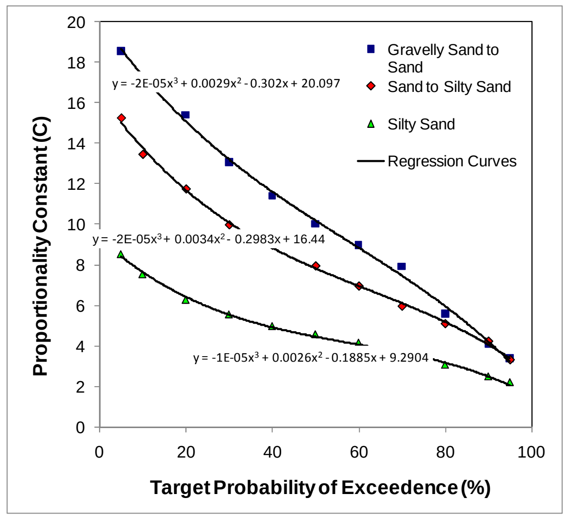


Figure 7. Variation of the proportionality constant (C) with the probability that field data will exceed the values predicted using Equation 5.

5 CONCLUSIONS

This study examined the applicability of various CPT-SPT correlations currently available in the geotechnical literature to calcareous sands in the Persian Gulf area. This was carried out by comparing these correlations with high quality CPT and SPT data collected from the UAE. Attempts were also made to develop region-specific correlations and to quantify the uncertainty in these correlations. The conclusions of the study can be summarized as follows:

- Existing CPT-SPT correlations based on grain size characteristics, such as D_{50} and fine content, are poorly applicable to the UAE sands. This was attributed to many deviations, such as the increased carbonate content and absence of SPT energy measurement, from the existing correlations.

- Existing CPT-SPT correlations based on soil classification techniques, such as the Soil Behavior Type Index (I_c), showed general agreement with the trend of field data. In addition, the scatter in field data was smaller compared to D_{50} and fine content based correlations.
- The ratio $(q_c/P_a)/N_{60}$, as determined from field data, for the UAE calcareous fine to medium grained sand was found to be significantly, 40 to 45%, higher than the values predicted using the existing correlations for siliceous sand.
- Risk-based CPT-SPT correlations were developed for the UAE calcareous sand based on the target probability that the actual field value will be higher than the predicted one.
- There is a need to collect additional high quality CPT and SPT data from the UAE area to verify and refine the finding of this study.

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