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Correlation between Shear Wave Velocity and Cone Penetration Test Data in Offshore Carbonate Soils

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Abstract **–** Empirical correlations between shear wave velocity and cone penetration testing data in soils may be used to predict shear wave velocity in absence of direct measurements. However, existing correlations in the geotechnical literature were usually developed based on data from silica soils. These correlations may lead to poor predictions in carbonate soils. This paper investigates correlations between shear wave velocity and cone penetration test data for carbonate soils. Data from site investigation campaigns at 22 different borehole locations within an offshore field in the Arabian Gulf were examined. The soils at these borehole locations are high in carbonate contents. Based on regression analysis, a correlation to estimate shear wave velocity as a function of cone tip resistance is proposed.

Keywords**:** Shear Wave Velocity, Cone Penetration Testing, Carbonate Soils

1. Introduction

The shear wave velocity (V_s) is an important soil parameter that can be used to estimate the low strain shear modulus (G_{max}). An accurate estimate of G_{max} is important for the evaluation and modelling of low strain soil behavior, which has applications in determining dynamic and static soil behavior. Direct measurements of V_s or G_{max} are preferred but may not be practical for some projects due to cost or logistical constraints. Hence, there has been sustained interest in indirect predictions of shear wave velocity from other in-situ data, especially cone penetration testing (CPT). The strain levels associated with the low strain shear modulus (on the order of 10^{-3} % or less) are orders of magnitude lower than the strains experienced by soils during cone penetration testing (shear strains associated with peak and remolded/residual shear strengths). However, both V_s and CPT data are primarily influenced by similar factors such as stress state, effective stress, voids ratio, stress history, cementation and aging, and thus similar trends between the two exist [1].

A number of different empirical correlations between V_s and CPT data exist in geotechnical literature [2]. These empirical correlations are developed either for a specific soil type [1], or for all soil types [3, 4, 5]. The correlation between V_s and CPT data also depends on the geologic age of the soil deposits and different correlations have been suggested for Holocene and Quaternary periods [2]. The inclusion of an initial voids ratio term in the correlation can significantly improve the shear wave velocity estimate [1, 3], however initial voids ratio measurement from soil samples may not always be feasible. Unfortunately, most of the existing correlations are based on data from silica soils. The use of these correlations in carbonate soils may lead to erroneous predictions of V_s. There is a lack of studies investigating the correlation between V_s and CPT data in carbonate soils.

This study compares CPT data and direct measurements of V_s in carbonate soils from the Arabian Gulf. The purpose of the comparison is to develop an empirical correlation between the shear wave velocity and cone penetration test data for carbonate soils.

2. Database

Shear wave velocity (V_s) and cone penetration test (CPT) data was compiled from 22 different borehole locations in an offshore field in the Arabian Gulf. The shear wave velocity measurements were made using P&S suspension logging. The shear wave velocity measurements were made from the seafloor to maximum investigation depths ranging from 50 m to 200 m below seafloor, at measurement intervals ranging between 0.5 and 3 m. The cone penetration testing was performed in downhole mode from seafloor to maximum investigation depths ranging from 30 m to 150 m below seafloor, at a standard measurement interval of 2 cm.

The geology in Arabian Gulf is shaped primarily by historic sea level fluctuations, resulting in a high degree of lateral variability in general. Most of the sediments are of biogenic origin with high carbonate contents. Due to desiccation, and reduction and increase in sea water level in the past, clays are generally over-consolidated and silts and sands are variably cemented, ranging from relatively uncemented to very well cemented deposits.

The site conditions at the 22 borehole locations were mostly dominated by clays with interbedded layers of sand. A small number of the borehole locations were dominated by sands. Thin layers of silt were encountered in a few rare cases. Carbonate contents were high and generally ranged between 30% and 75% for clays and between 60% and 95% for sands. Clays were lightly overconsolidated. Sands were usually cemented. The degree of cementation varied, and the sands encountered ranged from being very slightly cemented to well cemented. CPT refusals, where penetration stops due to achieving maximum thrust or tip resistance, were common in highly cemented sands.

During P&S suspension logging, the distance between the two receivers was fixed at 1 meter. For the purpose of a reasonable comparison, the cone tip resistance (q_c) data was also averaged over a depth of 1 meter. Out of the 22 borehole locations considered, 11 locations had CPT and P&S suspension logging performed in the same borehole, whereas the other 11 locations had CPT and P&S suspension logging performed in different boreholes (spaced between 4 – 40 m away). For these borehole locations, the depths that exhibited lateral variability were ignored. Additionally, for all the boreholes, only depths with uniform soil conditions over 1 meter were considered. Depths at which multiple soil layer types were encountered within 1 meter were ignored. A final number of 762 data points were selected for comparison and are presented in Fig. 1.

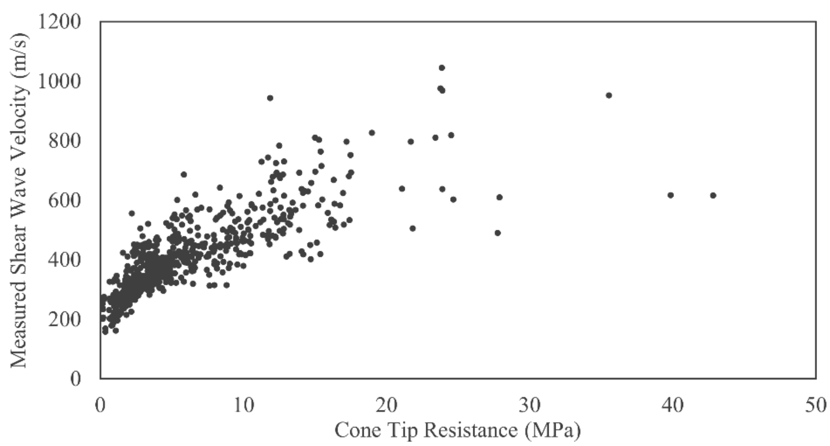

Fig. 1: Measured shear wave velocity against cone tip resistance averaged over 1 meter

3. Results and Discussion

Regression analysis of the final selected data points (n = 762), using the least squares method, resulted in the following correlation ($r^2 = 0.695$):

$$V_s = 24.6144\, q_c^{0.32978} \tag{1}$$

where, V_s is in m/s and q_c is in kPa.

The use of other variables from CPT data was also explored. Correlating shear wave velocity with total or net cone resistance (q_t or q_{net}) instead of cone tip resistance (q_c) didn't result in any improvement to the correlation. The effect of adding other variables, including Sleeve Friction, Overburden Stress, Depth and Soil Behavior Type Index, was investigated as well. The inclusion of these variables did not introduce any significant improvements compared to Eq. (1).

The predicted shear wave velocities (using Eq. (1)) were compared with the measured data and the results are presented in Fig. 2.

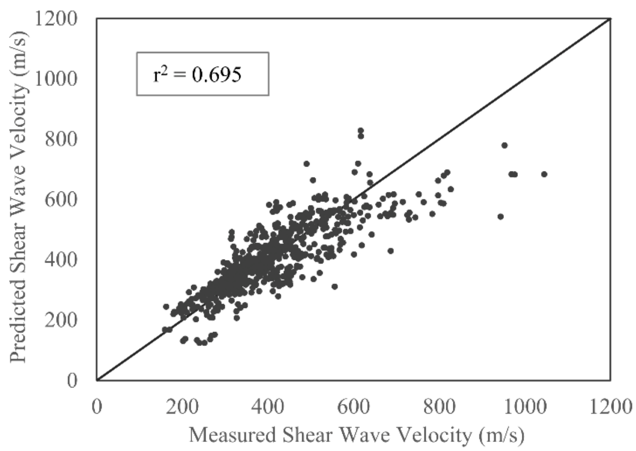

Fig. 2: Comparison between measured and predicted shear wave velocities.

For the purpose of verification, the correlation was applied to two independent borehole locations in the same field. CPT and shear wave velocity data were available for both locations. The data from these borehole locations were not included in the database used in the regression analysis, to allow for independent verification. The comparison of measured and predicted shear wave velocity for these two locations is presented in Fig. 3. It is clear that the shear wave velocities predicted using Eq. (1) provide a reasonable match with the shear wave velocities measured in-situ using P&S suspension logging. In comparison, correlations commonly used in the industry [3, 5], that were developed based on data from silica soils, underpredict the shear wave velocity.

A shortcoming of the dataset considered in this study is the lack of CPT data points in dense and/or cemented sands due to CPT refusal. Thus, the dataset only contains data from clays, silts and relatively loose and uncemented to slightly cemented sands and is biased towards these soil types. The correlation struggles to predict accurate shear wave velocities in dense and/or moderately to well cemented sands and rocks.

4. Conclusion

Shear wave velocity measurements and cone penetration test data from 22 borehole locations dominated by carbonate soils were compared. Based on regression analysis of the data, a correlation that expresses the shear wave velocity as a function of cone tip resistance is presented in Eq. (1). This correlation is shown to predict shear wave velocities reasonably well in clays, silts and loose sands with high carbonate contents. The correlation struggles to predict shear wave velocities in dense and/or cemented carbonate sands, due to the nature of the database.

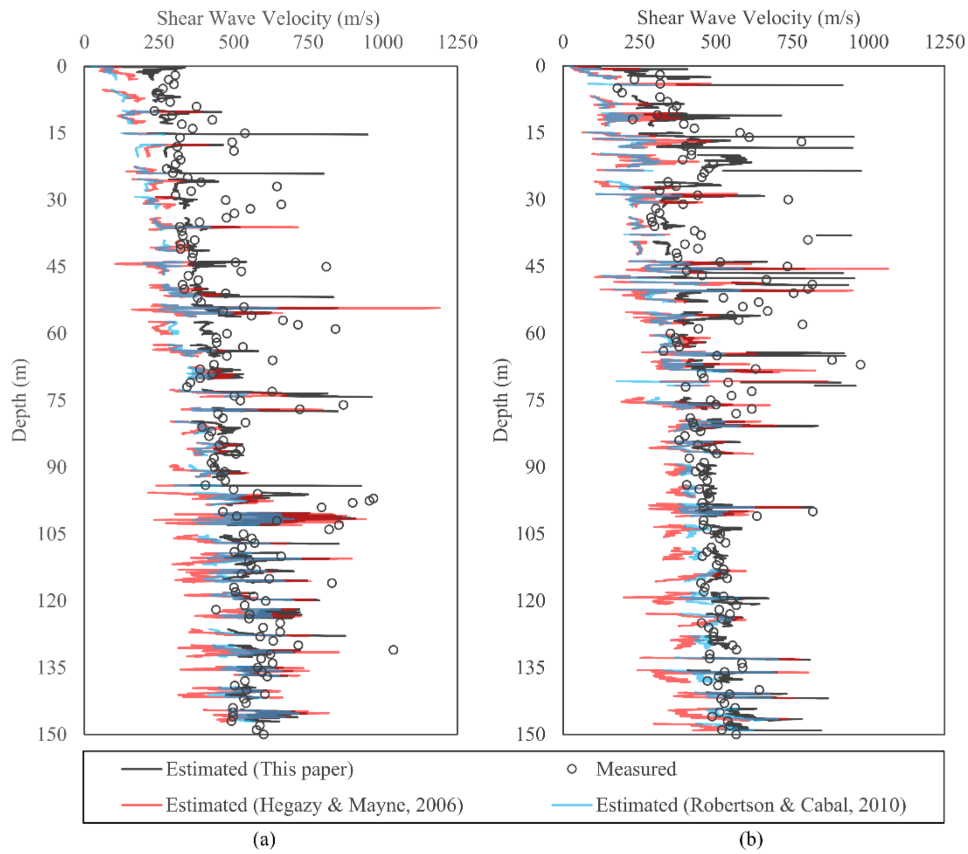

Fig. 3: Comparison of measured shear wave velocities with predictions from CPT data from two independent locations.

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