Prediction of shear wave velocity for offshore sands using CPT data – Adriatic sea

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ABSTRACT: Shear wave velocity (V_s) is a key parameter for seismic amplification analyses, and for assessment of liquefaction potential of offshore sands. A number of methods are available to measure V_s offshore, of which the seismic Cone Penetration Testing (CPT) usually proves to be the most effective. However direct V_s measurements are typically not included in the scope of work for offshore investigations, and the geotechnical design must rely on correlations to other soil parameters. This paper presents a correlation between the CPT data and V_s for medium dense offshore sands. The correlation combines the semi-empirical relationships between cone tip resistance and the variation of soil stiffness with the in situ stress. The prediction method was developed from a database of 23 sites in the Adriatic sea, offshore Italy. Where no direct measurements are available the shear wave velocity profiles can be delineated by means of the proposed correlation. However the inherent variability of the data confirms the benefits of direct measurements for critical projects.

1 INTRODUCTION

The shear wave velocity and shear modulus (G_{max}) are fundamental soil parameters. They are important in determining soil dynamic behavior and liquefaction susceptibility (Youd and Idriss 2001), as well as in static loading situations (Burland, 1989). The V_s can be measured using different in-situ tests such as seismic cone penetration test, seismic dilatometer test, downhole test, crosshole test, and spectral analysis of surface wave. Also, different empirical correlations have been developed between V_s and cone penetration test data. Baldi et al. (1989) correlated V_s in Italian sands with cone tip resistance (q_c) and the effective overburden stress (σ'_{vo}). Rix and Stokoe (1991) modified the above study and estimated G_{max}/q_c as a function of $q_c/(\sigma'_{vo})^{1/2}$. Mayne and Rix (1995) found that V_s in clays is statistically correlated with q_c and void ratio. Hegazy and Mayne (1995) updated the above correlations in sands and clays using additional data. More recently, Suzuki et al. (1998) found that normalized V_s to the corrected cone tip resistance in Japanese sites had a trend with the soil behavior type index (I_c).

Eni E&P of Milan, Italy have several concessions in the Adriatic sea, offshore Italy. D'Appolonia carried out a number of offshore geotechnical investigations on behalf of Eni for the design and installation of fixed offshore structures (D'Appolonia, 1993 to 2008). The direct measurement of shear wave velocity (V_s) was part of the scope of work for a limited number of investigations. This paper presents the V_s data gathered in the last 15 years in the Adriatic sea and proposes a simple q_c-V_s correlation for sands.

2 DATABASE DEVELOPMENT

The data presented in this paper were obtained at the 23 locations in the Adriatic sea shown in Figure 1.

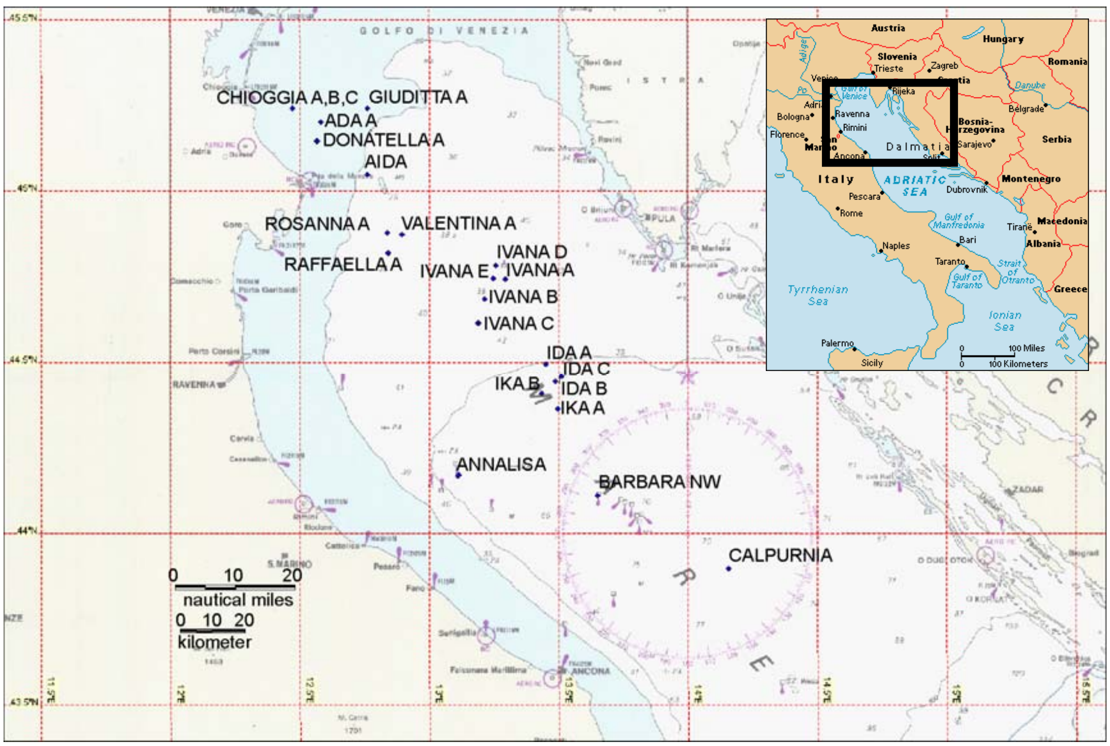

Figure 1. Site location map

Offshore drilling was carried out from the specialized Dynamic Positioning (DP) geotechnical vessels M/V Bavenit or equivalent. Drilling proceeded in accordance with normal offshore operating practice. A motion compensator stabilizes the drill string with respect to vertical movements of the vessel. Rotary drilling methods were used with an open faced drag bit. Fluid circulation was according to the open hole method, with cuttings returned to seabed. Reaction for in-situ testing operations was provided by a re-entry template. The typical depth of the investigation was 120 m below seafloor.

2.1 *Cone Penetration testing and V_s measurements*

The CPT data were obtained by means of a Wison piezocone penetrometer apparatus designed for offshore wireline operations in association with open hole drilling equipment. The penetrometer measures cone resistance, sleeve friction, and penetration pore pressure with automatic data logging. The cones used have a base area of 1,000 mm^2 and a friction sleeve of 15,000 mm^2. The device has a 3 meter stroke. Upon reaching the depth at which a cone penetration test is to be performed, drilling is stopped and the borehole flushed. The cone penetrometer unit is then lowered through the drill pipe to the bottom of the borehole. On reaching the special pre-drillbit collar, the unit latches mechanically into position. When latching is complete, the cone is pushed into the soil by a hydraulic ram. The rate of penetration is about two cm/s. During the test the output signals from the cone tip, the friction sleeve and the pressure transducer are recorded by the monitoring unit on deck. At the end of the test the unit is unlocked, retrieved and prepared for the next test.

The V_s data were recorded utilizing a seismic piezocone. Seismic piezocone testing consisted of recording shear waves at a known depth below the shear wave source. The shear waves were generated by a hydraulically driven spring hammer mounted on the seabed frame. The shear waves were received by a triaxial geophone incorporated in a conventional piezocone penetrometer. The seismic piezocone penetrometer is advanced to the required testing depth and stopped. The shear wave hammer is activated to generate shear waves and to trigger data recording. This procedure is repeated to make use of the so-called stacking method, which improves the signal to noise ratio.

The signals from the geophones are monitored by a seismograph, plotted for quality control, and stored on disk for further analysis. The raw data are filtered digitally to exclude the high frequency noise that may obscure the shear wave signal.

Using the filtered results, corresponding points in the wave pattern are indicated at subsequent testing depths. The difference in true distance between geophone and shear wave source is calculated for subsequent testing depths. The difference in distance divided by the difference in travel time for the corresponding points in the wave patterns gives the shear wave velocity for a depth interval. Repeating the test at various intervals in a boring allows a shear wave velocity profile to be constructed for a site. In general, V_s measurements were carried out at 1.5 m to 3.0 m intervals.

2.2 *Data example and compilation of the database*

Figure 2 and Figure 3 show an example of the q_c and V_s data utilized in this work and the predicted data range according to the methods described in the following. The database was compiled as follows:

- only V_s records representative of homogeneous sand conditions were considered;
- a corresponding average q_c was calculated for the same depth interval of the V_s record;
- each pair of q_c and V_s values was referred to the mid-depth of the corresponding measurements.

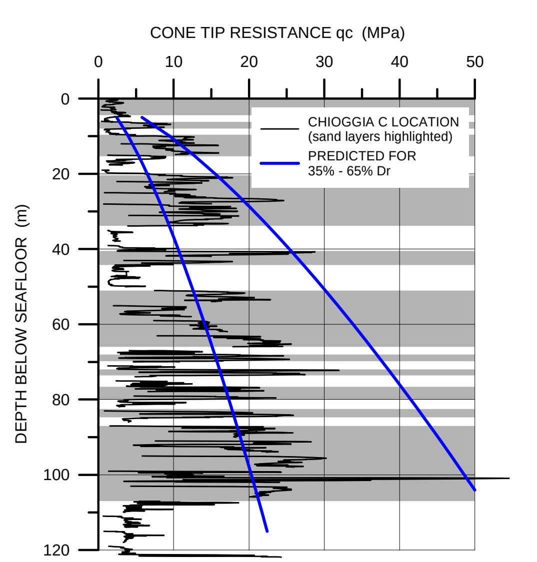

Figure 2. Example q_c data – Chioggia C

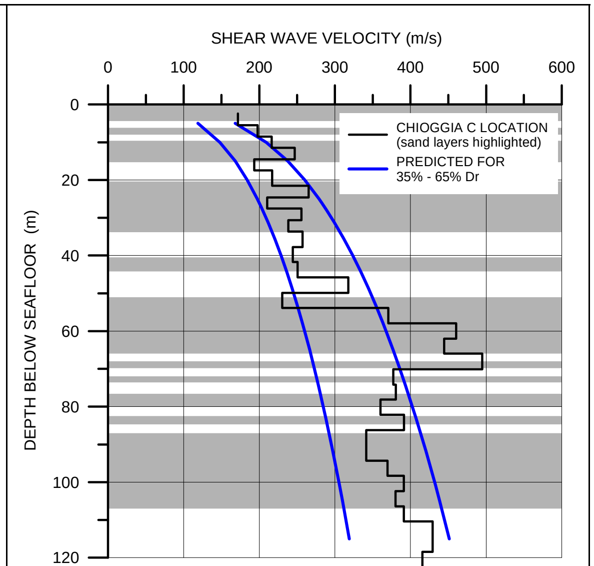

Figure 3. Example Vs data – Chioggia C

The summary of the q_c and V_s data for the 23 sites in the Adriatic is shown in Figure 4 and Figure 5, respectively.

3 GEOLOGICAL SETTING AND TYPICAL PROPERTIES OF THE SANDS

The Adriatic Sea is an epicontinental semi-enclosed basin characterized by a rectangular shape elongated in the north-west to south-east direction and a very low gradient of the seafloor. The northern Adriatic Basin can be considered the submarine continuation of the Po basin over a continental shelf area. Here, 7000 m of sandy and argillaceous beds deposited during the Pliocene. Most of the sediment is derived from erosion of the Alpine and Apennine chains, and are predominantly silica and micaceous. Plio-Quaternary geologic and geomorphologic processes have significantly changed the geography of the Adriatic Sea. During the Quaternary glaciations, sea level changes led to migration of the coastline, which was accentuated by the low shelf gradient. After a slow regression, the Adriatic reached a minimum elevation of 120 m below the current level during the most recent (Würmian) glaciation, about 18000 years B.P. The entire shelf was exposed to subaerial conditions and a fluvio-lacustrine plain developed. The successive rise in sea level, the Flandrian transgression, rapidly flooded the alluvial plain. During this process the continental deposits were partially eroded, reworked and covered by a thin stratum of marine sediments (Correggiari et al., 1996).

The sands encountered in the Adriatic sea typically have the following properties:

- USCS group: SP, SP-SM
- D_{50}: 0.2 to 0.3 mm
- Fines content: 3% to 10%
- Carbonate Content: 5% to 15% (silica to calcareous silica)

4 BACKGROUND FOR THE PROPOSED CORRELATION

This study is focused on deriving a simple correlation between uncorrected CPT data and V_s in sand. The use of more advanced correlations did not provide the benefit of simplicity of the method described below.

4.1 *Cone tip resistance versus in-situ effective stress*

The following q_c – relative density correlation was considered for offshore sands (Lunne and Christoffersen, 1983):

$$D_r = \frac{1}{2.91} \cdot \ln \frac{q_c}{61 \cdot \sigma_v'^{\,0.71}} \qquad (1)$$

where D_r is the relative density, q_c is the cone tip resistance in kPa, and σ_v' is the vertical effective stress in kPa. This equation can be reorganized as:

$$q_c = 61 \cdot \sigma_v'^{\,0.71} \cdot e^{2.91 \cdot Dr} \qquad (2)$$

where e is natural logarithm base (≈ 2.72).

Figure 4 shows the summary of CPT data and the range of q_c obtained from Equation (2) for relative density of 35% and 65%. Data show a good match with Equation (2).

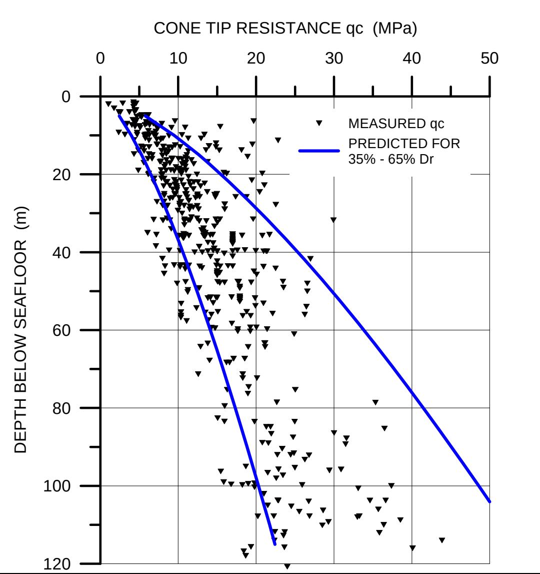

Figure 4. Summary of q_c data in sand – all 23 sites

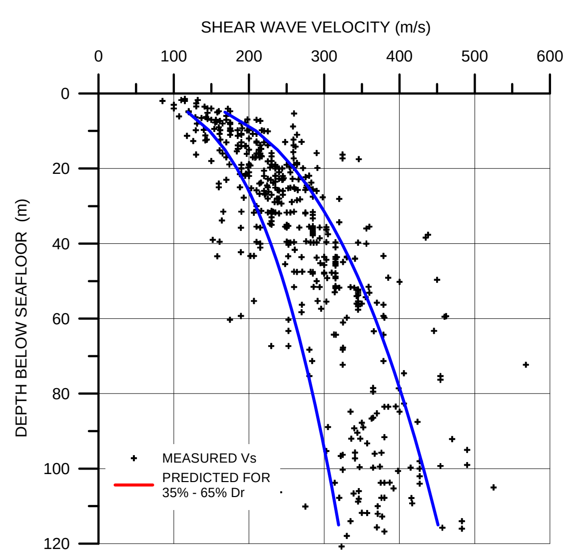

Figure 5. Summary of V_s data in sand – all 23 sites

4.2 *Shear wave velocity versus in-situ effective stress*

Several correlations are available in the literature for the prediction of V_s with depth in sands. A widely used correlation was proposed by Seed and Idriss (1970) in the form of Equation (3):

$$G_{max} = 1{,}000 \cdot K_{2,max} \cdot (\sigma_m^{'})^{\alpha} \quad (3)$$

where G_{max} is the shear modulus at small strain, σ_m' is the mean effective stress, both in pound per square foot; $K_{2,\ max}$ is a coefficient function of the relative density and α was equal to 0.5 according to the authors.

The shear wave velocity can be obtained from Equation (4):

$$V_s = \sqrt{\frac{G_{max}}{\rho}} \quad (4)$$

where ρ is the total, not the submerged, soil density.

The summary of shear wave velocity data in the Adriatic sands is shown in Figure 5. The figure also shows the predicted range of V_s according to Equations (3) and (4) considering $K_{2,max}$ of 37 and 56 for relative densities of 35% and 65%, respectively, and a value of α equal to 0.63.

5 DATA EVALUATION

Available data show that the cone tip resistance in the Adriatic sands is a function of the in situ vertical stress to the power of 0.7 (Equation 2 and Figure 4), while the shear wave velocity is a function of the in situ mean stress to the power of 0.3 (Equations 3 and 4, and Figure 5). The ratio between the shear wave velocity and the cone tip resistance should therefore be correlated to the in situ effective stress to the power of 0.3/0.7, i.e. 0.43. Figure 6 shows that the data follows this trend: the mean linear trend and the ±30% range cover most of the data.

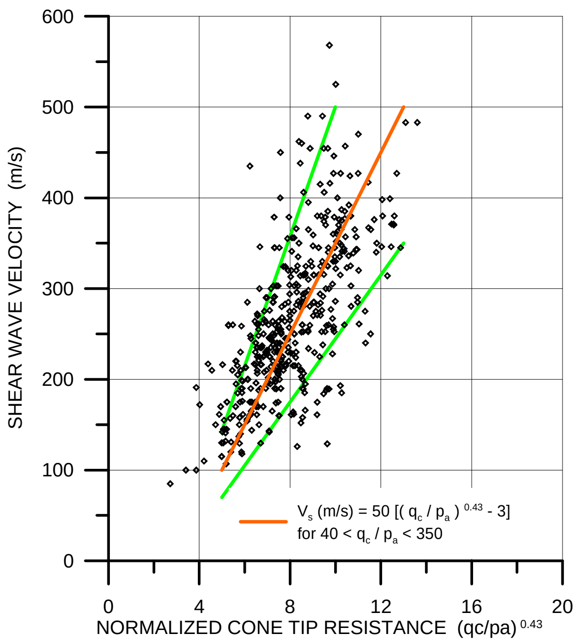

Figure 6. Linearization of the $q_c – V_s$ database

The mean trend can be described according to the following equation:

$$V_s = 50 \cdot \left[(q_c / p_a)^{0.43} - 3 \right] \tag{5}$$

developed for $40 < q_c / p_a < 350$

where p_a is the atmospheric pressure and V_s is expressed in meter per second.

6 CONCLUSIONS

This paper presents a site-specific q_c-V_s correlation developed for the medium dense offshore sands encountered in the Adriatic sea. A simple correlation is obtained from available data, based on the cone tip resistance. Evaluation of void ratio or other input is not required. The proposed correlation is valid for q_c / p_a comprised between 40 and 350.

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