Application of Offshore Seismic CPT data for Soil Stiffness Interpretation

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ABSTRACT

One of the most important dynamic soil parameters is the shear wave velocity (Vₜ), used mostly for calculating the shear modulus (G), based on a simple elastic relationship with the mass density. The methods to derive the shear wave velocity include direct measurement by use of in-situ geophysical tests (seismic CPT, PS Logging, etc.), laboratory tests, or by using empirical and site-specific correlations from cone penetration tests (CPT). For the detailed design of an Offshore Wind Farm (OWF), a site investigation has been conducted using static and seismic CPT, the later for the measurement of the shear wave velocity. In addition, PS logging (down-the-hole acoustic probe) and several laboratory bender element (BE) tests have been carried out, enabling an evaluation and application of the site-specific CPT-Vₜ correlation. The application of the in-situ methods will be discussed with regards to the limitations, and important recommendations will be given to overcome the challenges during offshore soil investigation.

Keywords: seismic CPT, shear modulus (G), shear wave velocity (Vₜ)

1. INTRODUCTION

Estimation of the shear wave velocity (Vₜ) through different measurements or correlations, is an important component of various site response analyses and soil-structure interaction. The compression wave velocity (Vₚ) and Vₜ have been used to describe the elasticity of the soils, to predict the soil dynamic response, due to earthquake or other vibrations. The importance in the accuracy of estimating the Vₜ is related directly with the equations from elasticity theory, applied for calculating the shear modulus (Gₘₐₓ), Poisson’s ratio (μ), Young’s modulus (E), etc.

In this paper, several aspects for the application of offshore seismic CPTs for soil stiffness interpretation, are discussed. For the detailed design of an Offshore Wind Farm (OWF), full interpretation of the seismic CPT, including estimation of shear wave velocity and derivation of the shear modulus have been carried out. A detailed assessment of the existing site-specific correlations, based on the measured Vₜ from seismic CPT and other in-situ or laboratory tests, has been performed.

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2. SITE DATA (IN-SITU AND LABORATORY MEASUREMENTS)

2.1. In-Situ Data

As part of an offshore site investigation campaign, different in-situ and laboratory tests have been carried out. For the considered location, down-the-hole CPTs (DTH-CPTs), seismic CPTs and several laboratory tests (classification and advanced) have been performed.

The chosen CPT (CPT-1) and the available soil density measurements are shown in Figure 1.

Filtering of the CPT data was considered necessary in order to remove pick measurements.

The shallow geology of the area is interpreted to comprise of three main units. The first Holocene unit has been seen with a thickness of maximum 4.5 m below seabed and comprises of very soft, low strength silty and gravelly organic clay. The second unit comprises Pleistocene sediments and consist of glacial deposits (glacial clay, sand, gravel and till). Both Holocene and Pleistocene are Quaternary sediments. A geological description of the units, together with the depths where Vs measurements have been performed, is shown in Figure 2.

2.2. Normalized Soil Behaviour Type (SBTn) chart

Due to increasing effective overburden stress with depth, the CPT data requires normalization. The normalized chart (Robertson, 2010) provides a more accurate identification of the soil type, than the non-normalized one (Robertson, 2009). However, a slight difference is expected for the presented CPT, with maximum in-situ vertical effective stress of about 150 kPa.

Soil classification based on the interpreted SBT according to (Robertson, 2010) has been performed and presented in Figure 3 and Figure 4. The charts have been created by using a self-developed visual basic form implemented in excel.

The chart proposed by (Robertson, 2010) is able to identify general trends in ground response, such as, over consolidation ratio (OCR), age and cementation for sandy soils, increasing stress history and soil sensitivity (St) for
cohesive soils (Robertson & Cabal, 2015). All the above-mentioned parameters play also an important role in the transmission of shear wave velocity ($V_s$).

![Figure 3. Normalized SBTn Index ($I_c$) – CPT-1](image)

3. DETERMINATION OF SMALL STRAIN SHEAR MODULUS ($G_{\text{MAX}}$) USING $V_s$

The determination of the soil stiffness parameters needs a very careful consideration of the associated level of strains. Various geophysical methods and laboratory testing could be used to measure the shear wave velocity. In all the cases, it is important to highlight the fact that $G$ is highly dependent upon the strain level.

All the geophysical methods are testing techniques, which provide low strain in-situ compression and shear wave velocity measurements. At low strain levels (less than about $10^{-4}$ %) the shear modulus in soil is constant at its maximum value $G_{\text{MAX}}$ (Andrus, et al., 2007). The shear response for different strain levels could be estimated by using laboratory tests or different published theoretical degradation curves of the ratio $G/G_{\text{MAX}}$. The shear modulus ($G_{\text{MAX}}$) is a parameter calculated...
based on the $V_s$, using a simple elastic relationship as given in Equation (1).

$$G_{\text{max}} = \rho V_s^2$$  \hspace{1cm} (1)

where soil density $\rho$ is the total unit weight of soil divided by gravity (9.81 m/sec$^2$). $G_{\text{max}}$ has units of force per length squared and can also be measured in the laboratory by using resonant column or bender element tests.

4. MEASUREMENT OF $V_s$

$V_s$ could be measured by using different in-situ geophysical methods as well as by laboratory tests. The in-situ methods are divided into invasive and non-invasive. (Wair, et al., 2012). Invasive methods require drilling on the ground and include different downhole and cross-hole logging, suspension logging, etc. A very rapid and cost effective invasive method is the seismic CPT (SCPT). Non-invasive methods do not require drilling or penetration into the ground. These methods include different seismic refraction and spectral analysis of surface waves (SASW).

Same as for the other types of geotechnical laboratory tests, also for the measurement of the $V_s$, high quality undisturbed samples are required. This quality of the testing is very often not possible to be achieved, especially for sandy soils.

In this paper, only the measurement of the $V_s$ by use of SCPT is discussed. The interpretation and analysis of the data is based on an offshore SCPT measurement. In addition, some results of other invasive methods such as PS suspension log probe and bender element test have been used.

4.1. Seismic CPT (SCPT)

The SCPT measurements have been carried out in conjunction with an offshore drilling campaign. For the measurements of the $V_s$, Geo’s state-of-the-art shear wave module (Geo SBF-Hammer) has been used. Geo’s $V_s$ module for seismic down-the-hole SCPT (DTH-SCPT) is an integrated part of the seabed frame (see Figure 5). The seismic “hammer” (Figure 6) is controlled and operated by the CPT operator on-board of the drilling vessel.

Figure 5. The Seabed Frame (the seismic hammer fits in the cavity to the right)

Figure 6. Geo’s seismic hammer unit

In combination with Geo’s fast operating DTH-CPT system, the Geo SBF – Hammer provides essential data for different offshore site investigations for wind farms, jack-up rig installations, platforms, subsea structures and bridges.

4.2. Data acquisition system

The data acquisition system used is A.P. Van den Bergs Icone and the $V_s$ measurements were recorded using a seismic piezocone. With the Icone seismic
module, the digital cone is turned into a seismic or SCPT cone.

The standard Icone seismic module contains three accelerometers to receive shear waves (left, right and compression waves). The main principle of the SCPT testing consists of recording shear waves at a known depth, below the source (seismic hammer). First, the shear waves are generated by a driven spring hammer mounted on the seabed frame. These shear waves are later received by a geophone incorporated in the conventional piezocone penetrometer.

The SCPT is pushed down to the required depth and then the hammer is activated to generate shear waves. All the signals received on the geophone are monitored by a seismograph. For the required testing depth, the distance between the source and the geophone is a known parameter. The difference in distance between the geophone and the source is calculated for different testing depths. This distance, divided by the difference in travel time for each depth gives the shear wave velocity at that depth interval.

4.3. Processing shear wave velocity signals

The commercial software SPAS 2009 v.2.0.2.69 (Seismic Processing and Analysis of Signals)(SPAS 2009 v.2.0 - GeoLogismiki, 2009) has been used to process and analyse the measured signals.

After importing the signals, the first step in the processing of the data is to check for signals repeatability. The program allows to select multiple signals from the same depth. In this way is possible to identify “bad” signals and easily remove these by unchecking.

The quality of the signal is primarily affected by the efficiency of the source hammer, the energy level, and also from the noise generated by the seabed drilling system. The ambient noise that comes from the drilling system should be minimized in order to increase the signal-to-noise ratio (SNR). Considering the different challenges that come during an offshore site investigation, it is impossible to eliminate all the sources of background noise. In order to increase the quality of the signal data, digital filtering techniques have to be used. However, it is to be mentioned that the filtering technique, compared with other ways of improving signal quality, is the last means of improvement. The filtering technique is based on cutting-off the frequency filters (Figure 7 shows the filtering technique applied to one SCPT measurement at 3.0 m depth).

![Figure 7. Signal filtering using SPAS 2009, SCPT measurement at 3.0 m depth.](image)

The most important aspect in applying the digital filtering technique, is to identify the major dominant noise frequencies. A wide band-pass filter covering the range of predominant frequency is recommended (e.g. 10 to 50 Hz)(Nguyen, et al., 2015).

The measured data have been filtered and processed in order to estimate the shear wave velocity. The depths where SCPT measurements have been successfully performed, are shown in Figure 2.

4.4. Bender Element Test

In addition to SCPT, bender element tests (BE) have been carried out in laboratory in
order to measure $G_{\text{max}}$. The depths of the tested samples are shown in Figure 2.

4.5. PS Logging
The PS logger is a high energy, low frequency acoustic probe, designed to measure compression and shear wave velocities in fluid filled boreholes. PS logging have been carried out at the investigated borehole at depths starting from 14 m below seabed. For this study, only the measurement of PS logging from 14 to 15 m will be considered.

4.6. Vs measurements
The results of Vs measurements from SCPT, BE and PS logging, together with the corresponding depths are given in Table 1.

<table>
<thead>
<tr>
<th>Method</th>
<th>SCPT</th>
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<th>BE</th>
<th>Method</th>
<th>PS</th>
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<td>Vs [m/s]</td>
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5. REVIEW OF VS CORRELATIONS WITH CPT

5.1. General
Several authors and researchers have studied and published relationships between CPT and $V_s$. The correlations have been developed based on different $V_s$ measurements and considering other data such as: geological age, deposits, OCR, test locations, etc.

The main CPT parameters used for correlations include: depth (D), tip resistance ($q_c$), sleeve friction ($f_s$), soil behaviour type index ($I_c$), effective stress ($\sigma'_{v}$), etc. The published CPT-$V_s$ correlations are generally developed for specific soils types (i.e., “Sand” or “Clay”), but also for “All soils”. According to (Wair, et al., 2012), when comparing the correlations developed for specific soils with the correlations developed for “All soils” it results that statistically both methods perform similarly. However, the soil type-specific method under-predicted $V_s$ by 8% and “All soils” method under-predicted by 3%. In addition, the soil type-specific method produced spikes in the $V_s$ profile, at transition soils between layers. As a result, the “All soils” method is considered more applicable(Wair, et al., 2012).

This study focuses on only three most recent CPT-$V_s$ correlations, developed for “All soils” and based on a relatively independent and large numbers of data pairs. Also, only the correlations developed for Holocene and Pleistocene age soils have been considered. The correlations used have been presented from(Robertson, 2009), (Mayne, 2007) and (Andrus, et al., 2007).

5.2. (Robertson, 2009)
(Robertson, 2009) developed a general correlation CPT-$V_s$ based on 1035 data pairs, from Holocene and Pleistocene soil sites. The general expression of $V_s$ is given in Equation (2).

$$V_s = \left[ 1.0^{0.106I_c + 0.22} (q_t - \sigma_{\text{in}})/\rho_a \right]^{0.22}$$ (2)

where $q_t$ is the corrected cone tip resistance, $\sigma_{\text{in}}$ is the in-situ vertical stress, $\rho_a$ is the atmospheric pressure and $I_c$ is the SBT index. The SBT zones have been calculated for each layer, as presented in Figure 4.
5.3. (Mayne, 2007)
Initially, (Mayne, 2006), proposed an “All soils” correlation between $V_s$, CPT and $f_s$ based on regression of a large dataset from different sites.

(Mayne, 2007) updated the correlation by considering the logarithm of $f_s$, rather than the natural logarithm that was proposed originally in (Mayne, 2006). The general form of the correlation is given in Equation (3).

$$V_s = 118.8 \log (f_s) + 10.3$$  \hspace{1cm} (3)

The correlation was derived from a database that included sands, silts, clays, as well as mixed soil types.

5.4. (Andrus, et al., 2007)
(Andrus, et al., 2007) proposed a correlation applicable to all soils and based on a dataset of 229 CPTs and $V_s$ measurements. The dataset included 72 data soils of Holocene geologic age, 113 data of Pleistocene and 44 data of Tertiary age. The majority of the $V_s$ measurements were performed using the SCPT.

For the regression analysis, (Andrus, et al., 2007) has taken into account several previous publications and only the ones with lower standard deviation of the residuals have been used. Based on the combined Holocene and Pleistocene dataset, the best-fit regression equation for predicting $V_s$ in m/s is given from Equation (4).

$$V_s = 2.63d_2^{0.039}D_1^{0.012}D_2^{0.128}SF$$  \hspace{1cm} (4)

where $SF$ is a scaling factor that takes into account the reference age for the combined Holocene and Pleistocene data.

For Holocene soils the value of $SF$ varies from (0.88-0.92) and for Pleistocene soils from (1.11-1.12). In our calculations, for the Holocene layer (0.0 - 4.5) the SF factor has been chosen equal to 0.9 and for the Pleistocene layer was chosen equal to 1.1.

6. INTERPRETATION OF THE RESULTS
The considered correlations have been applied to the available CPT data in order to estimate the $V_s$. The calculated $V_s$ for each correlation was compared to the measured $V_s$ values, determined from the SCPT, BE and PS logging. A general overview, showing the comparison between the measured and the correlated $V_s$, is given in Figure 8.

![Figure 8. Comparison between measured and estimated $V_s$ profiles.](image-url)

As seen from Figure 8, the general trend of the $V_s$, suggested by the measured values, has been captured by the considered correlations. However, differences in predicting the $V_s$ are evident and can be seen through the depth. Generally, (Robertson, 2009) and (Andrus, et al., 2007) show a more similar prediction, compared with (Mayne, 2007).
An under-estimation of the $V_s$ could be seen for the first layer from (Robertson, 2009) and (Mayne, 2007). This under-estimation is expected and mentioned also by (Robertson, 2009). However, at the end of the CPT, these methods over-estimate the predicted $V_s$. (Mayne, 2007) correlation looks visually closer to the measured values and it has captured almost all the trends suggested by the measured data. A tentative explanation of this could be the fact that (Mayne, 2007) correlation follows the trend of the $f_s$, which in this case, comply well with the measured data.

In order to have a better quantification of each correlation method, the $V_s$ is plotted in terms of the ratio between the estimated $V_s$ to the measured one. This ratio is considered as $V_s$ bias. Presented in this way, a ratio equal to 1, would assume an ideal correlation, where the estimated is equal to the measured. Moreover, a ratio less than 1, represents an under-estimation of the $V_s$ and a ratio larger than 1 represents an over-estimation.

The results for each method have been plotted in charts and are shown in Figure 9 for (Robertson, 2009), in Figure 10 for (Mayne, 2007) and in Figure 11 for (Andrus, et al., 2007). For the available dataset, (Robertson, 2009) correlation under-estimates the $V_s$ with a mean bias of $\mu=0.85$ and corresponding coefficient of variation $COV=23\%$. (Andrus, et al., 2007) correlation follows the same trend as (Robertson, 2009), and has shown almost the same performance ($\mu=0.89$, $COV=24\%$). (Mayne, 2007) correlation, presented in Figure 10, appears to be most applicable for the available $V_s$ measurements. The performance of this correlation show plotted data close to 1, with a mean value of $\mu=1.03$ and $COV=6\%$. However, the relatively low number of the available data, does not allow for a more definitive conclusion regarding which method could be considered more accurate for these specific soil conditions.
Recommendations given from (Wair, et al., 2012) suggest that for Quaternary soils (Holocene and Pleistocene) the $V_s$ could be estimated by taking the averaged value derived from (Robertson, 2009), (Andrus, et al., 2007) and (Mayne, 2007). In all the cases, where is possible to know the ageing of the soil and the geology, it is important to apply the ageing factors on Holocene (0.88 – 0.92) and on Pleistocene (1.11 – 1.12). For same soil conditions with same CPT penetration resistance, the $V_s$ in Holocene could be (22-26)% smaller than in Pleistocene deposits (Andrus, et al., 2007).

In the cases where it is not possible to get samples or identify the subsoil geology, the charts developed by (Robertson & Cabal, 2015) could help to evaluate the CPT data with regards of estimating the soils deposits age.

In Figure 12 is given an evaluation of the normalized $V_s$ for Holocene and Pleistocene age soils, according to (Robertson & Cabal, 2015).

According to (Robertson & Cabal, 2015), younger deposits, such as Holocene age soils, tend to plot towards the centre and lower left of the SBT$_n$ charts given in Figure 12 (first Holocene layer is plotted in red triangles). Older soils, such as Pleistocene, tend to plot toward the upper, right part of the chart (second Pleistocene layer is marked with blue squares). These results highlight the known fact that the shear wave velocity is sensitive to age and cementation and older deposits have higher shear wave velocity than younger deposits.

The calculation of the small strain shear modulus ($G_{max}$) have been carried out according to Equation (2). The correlation of $V_s$ given from (Mayne, 2007) and the soil density measurements given in Figure 1, have been used. The measurement of the $G_{max}$ from BE tests using the measured $V_s$ are also plotted.

![Figure 12 Evaluation of $V_s$ for Holocene and Pleistocene soils (Robertson & Cabal, 2015)](image12.png)

![Figure 13 Measured and estimated $G_{max}$](image13.png)
7. CONCLUSIONS

Important aspects in measuring the $V_s$ from the SCPT tests, processing of the data and discussing the application of existing site specific $V_s$-CPT correlations, are given in this paper.

A particular care must be given to the SCPT measurements during the offshore site investigation. The frequency of the seismic hammer is an important parameter that helps to filter out the dominant noise frequencies.

An engineering judgement is needed before the application of the available CPT – $V_s$correlations. The $V_s$ is also very much dependent on the deposits age of the soils and the developed correlations in general have been derived for soil data of a specific soil deposits age, such as Holocene or Pleistocene. For this reason, the ageing scale factors must be applied to the corresponding soil.

Measurement of the $V_s$ by using SCPT or other geophysical testing, including BE tests in the laboratory, provides low strain in-situ compression and shear wave velocity measurements. The shear modulus ($G$) is highly dependent upon the strain level, and the determination of the dynamic soil stiffness properties, needs a very careful consideration of the associated level of strains.

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REFERENCES


