Evaluation of the challenges present in obtaining, processing and interpreting useful data from offshore seismic cone penetration testing

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ABSTRACT

The Seismic Cone Penetration Test (SCPT) is an essential tool for establishing in-situ shear wave velocity (v_s), which is then used to establish profiles of Small Strain Shear Modulus (G_{max}), a direct input parameter to the design of offshore wind turbine foundations. Performance of SCPT offshore presents greater challenges than on land and each offshore site investigation contractor uses their own different non-standard equipment to try to address these challenges. This contributes to the multiple areas of uncertainty in the assessment of wave arrival time and distance, which can result in less reliable data sets. Additionally, a variety of data processing and interpretation methods are used across the industry, the benefits and limitations of which must be understood if one is to specify, plan or undertake such testing. The authors provide a review of methods of acquiring data, the equipment required and the different processing and interpretation methods available, specifically comparing true interval straight ray analyses with pseudo interval true ray path analyses and the different processing steps which can be taken to increase reliability in datasets.

Keywords: Seismic Cone Penetration Test (SCPT); Small Strain Shear Modulus (G_{max}); Shear wave velocity (v_s); Offshore; Site Investigation.

1. Introduction

In recent years, the increase in offshore windfarm development and modern methods of design (Byrne et al 2017) has driven advances in designers requiring a reliable understanding of small strain stiffness (G_{max}) to aid with design of large diameter foundation piles. Offshore, there are two methods primarily used to determine G_{max} in-situ, those are P-S suspension logging and SCPT. A comparison of these two methods is provided in Masters et al 2018.

In-situ determination of G_{max} relies on measurement of shear wave velocity, combined with known or estimated soil density in the following equation.:

$$G_{max} = \rho \times {v_s}^2$$

Where

ρ	is soil bulk density
v_s	is shear wave velocity

Profiles of G_{max} gained from SCPT on site are commonly combined with laboratory measurements made through bender elements or resonant column apparatus on high quality soil specimens carefully consolidated to their in-situ effective stress. These too are then often combined with empirically derived values of G_{max} from Piezo Cone Penetration Testing (PCPT). When the in-situ testing is of sufficiently high quality, empirical correlations with PCPT data can be developed on a site-specific basis most simply using easy to implement linear regression techniques as outlined by Fitzpatrick et al (2023) and Teng et al (2023).

Beyond v_s and G_{max}, SCPT is used to establish compression wave velocities (v_p), and in combination with the v_s, further engineering parameters may be established, i.e. Young's Modulus, Bulk Modulus and Poisson's Ratio. On its own, v_p is often used to validate two-way travel time assumptions in seismic profiles, helping with stratigraphical unitization and thus helping to package the soil profile up into layers of different behaviour for consideration in foundation analysis.

In this paper, the authors provide an insight into many areas of uncertainty in the gathering and processing of data from SCPT, the equipment used, the parameters gained and recommendations for post processing methodologies.

2. Uncertainty in wave velocity and parameter derivation

Offshore, SCPT is performed in down the hole mode using wireline SCPT tooling during the drilling of a borehole, and in seabed mode with the SCPT tooling pushed into the seafloor in a single long push from seabed. There are also 2 configurations for the positioning of the seismic source; a) on the drilling template / seabed frame (SBF) or b) on a separate source skid, deployed separately and located on the seabed a known distance from the SBF. Advantages and disadvantages of both are discussed in Masters et al 2018.

2.1. Conventional sources of uncertainty

Performance and interrogation of SCPT on its own does not yield seismic wave velocities. Velocities are established by measuring the arrival time of seismic waves at a receiver (the Seismic Lance) and measurement of a distance between the receiver and the origin of the waves: the seismic source. Reliable assessment of wave velocities therefore can be achieved through ensuring; repeatable triggering of the seismic source, production of repeatable waveforms (to enable stacking if necessary), the source having sufficient energy to transmit energy to the depths being investigated, high quality receiving sensors (geophones or accelerometers) which have been calibrated, accurate depth (z) determination, lateral offset certainty and suitable processing methods which are recommended to include true ray path / ray tracing methods where the source is sufficiently offset from the centreline of the CPT on a separate skid (Baziw 2002, Soage Santos et al 2023).

2.2. Uncertainty from sampling frequency

Current proposals in industry regarding sampling rate might be based on variations in sampling frequencies depending on project requests and on uncertainties at the time of obtaining v_p and v_s values (Koreta at al (2022). For example, a sampling frequency of 20kHz is often requested in order that accuracy of first arrival times can be established within 10th of a millisecond. Nevertheless, these proposals are strongly oriented to time domain analysis; the authors consider it valuable to explore seismic signal processing in other domains and approaches, such as the implementation of the Fast Fourier Transform (FFT) for signal processing in the frequency domain.

To assess the quality and characteristics of the datasets obtained offshore it is important to understand the use and reliability of each dataset, hence, the recording features have become one of the most discussed and strict requirements for offshore SCPT performance. For purposes of ensuring the quality required for signal processing of offshore datasets, the set-up and utilized sampling rate of the SCPT acquisition system can be based on the Shannon-Nyquist sampling theorem.

In essence, the body waves generated by the active source are naturally continuous signals, however, to get the key properties of those continuous signals while they are converted to their digital discrete form can be challenging due the complex nature of the body wave itself (P or S wave). Another important component of the recording is the noise frequency content not belonging to the body waves. Noise is commonly encountered as low frequencies below 350Hz from the offshore environment originating from currents or weather effects, and very high frequencies usually >4kHz, depending on the ambient noises and the acquisition system itself. These low and high frequency noises are identifiable during the pre-triggering portion and at the end of the frequency content of the recorded trace. Those mechanical alterations into the seismic traces can be originated due to different factors, originating from the marine and operational environment. In addition, there is the effect of distortion of the entire record (seismic body wave signal plus noise collection) generated by other complexities beyond the scope of this work.

Based on the knowledge of the existence of noise and the uncertainty regarding the actual frequency content of the body waves of interest for SCPT processing, the seismic test shall be performed prepared to record noises and mechanical vibration generated by the active source percussion. According to Nyquist (1928) the base rule to record a signal is by means of using a sampling frequency of 2ωHz, with ω being the highest frequency of the frequency content of the signal, including in this analysis the collection of frequencies correspondent to external factors such as ambient noise or others, and also, considering the possible development of aliasing, which creates a false low frequency signal as a result of down-sampling the recorded wave.

Subsequently this theorem was complemented by Shannon (1940) and it is now recognized that the sampling frequency has to be at least 2ωHz to reconstruct a sinusoidal wave efficiently from a finite number of samples.

As an example, Figure 1 illustrates the frequency content of an offshore seismic trace, presented in frequency domain through FFT method.

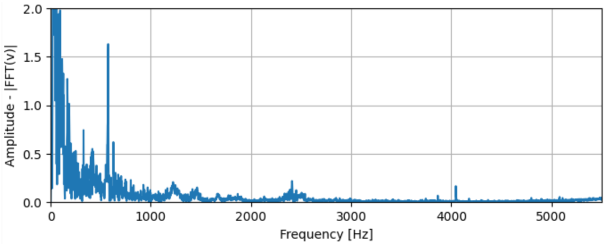

Figure 1. Frequency content in FFT from SCPT seismic signal.

The original discrete signal from Figure 1 belongs to a collection of more than 500 seismic traces and it comprises the frequencies of a body wave originated from a horizontal hammer shot, as well as the frequencies correspondent to the main sources of noise (low and high frequency noises), being the type of noise constant all along the different traces recorded in the SCPT from the selected site. The low and high frequency noises from Figure 1 are part of the recording from the start, before the pre-trigger portion, and remain until the end of the wave; many assumptions can be made regarding the nature of those two complex groups of noises, nevertheless, the thorough study of the behavior of electrical and mechanical noise are outside the scope of this specific work.

The study signal shows the frequency domain of a SCPT recording at sampling rate of 16kHz (0.0625ms). Additionally, Figure 1 illustrates the collection of frequencies with the highest frequency content at 5.1kHz. This identification of the frequency content is paramount for ensuring good quality measurements and based on Shannon-Nyquist sampling theorem, a sampling frequency beyond 10.2kHz should suffice for signal processing purposes.

One of the benefits of making these kinds of assessments is to provide confidence that the acquisition sampling rate was adequate for the purpose. Additionally, there is a lower computational cost in data acquisition, processing and in site and desktop QAQC processes when lower frequency acquisition is enabled.

An assessment of the type given here may be carried out during the first round of shots while using horizontal and vertical hammers in order to verify or reconsider the sampling frequency required for testing based on real conditions during the acquisition. So far, it is taken as granted that up-sampling a seismic trace is a practice that ensures the good quality of the offshore data, nevertheless, the precise effects of it have to be studied in detail as a manner of calibration of the uncertainty implied by effects of sampling.

More thorough review of Shannon-Nyquist theorem application, and the effects of up-sampling and aliasing, are outside the scope of this paper.

2.3. Trigger timing and arrival time uncertainty

Assessment of trigger repeatability by comparison between stacked sourcewaves against multiple unstacked sourcewaves was performed by Koreta et al (2022) during field trials illustrating up to 2% error.

For dual array systems, it is necessary for both sensors to be identical, providing an identical response. Without this certainty, the application of true interval analyses approaches will not be reliable. If uncertainty exists about differing responses, checks may be made to derived velocities by performing comparison pseudo interval analyses, providing that depth accuracy is sufficiently controlled.

Beyond the uncertainties imposed by digital filtering discussed in section 2.4 below and the discussion in Section 2.2 above, consideration for external coherent and random noises from the marine environment and vessel operations are described in Gibbs et al (2018).

Additionally, near field effects distorting waveforms can present a challenge for arrival picking especially for equipment arrangements where the source is located on or very near the SBF.

2.4. Uncertainty due to digital filtering

In SCPT we are looking to establish the response of the soil. Unless we separate any noise from the response of the soil, we cannot achieve anything useful. Interpretation of SCPT data requires digital filtering of seismic waves, as all the waves recorded invariably include background or ambient noise overlapping the sourcewave signature. To remove coherent noise, which is a type of ambient noise; multiple wave stacking method can be used. However, random noise cannot be removed by this process. Hence, digital filtering of noise from raw wave data is an essential part of data processing to identify main wave arrivals of shear and pressure waves.

There are two categories of digital filters that are often used for this purpose; Finite Impulse Response (FIR) and Infinite Impulse Response (IIR) filters. Both categories of filter incorporate phase shift in their response, which means they displace/distort the signal in the time domain by shifting the signal from its original position in time. Phase shifting behaviour introduces the uncertainty regarding accuracy of determining the arrival of seismic waves and resulting wave velocities. To reduce the uncertainty relating to filter use, it is crucial to use a filter which has negligible phase shift (these filters are known as Zero Phase Shift). The recommended filter type is Finite Impulse Response (FIR) as it can be designed to have linear phase. This means that effectively no phase distortion is introduced into the signal to be filtered, as all frequencies are shifted in time by the same amount – thus maintaining their relative harmonic relationships (i.e. constant group and phase delay).

There is no standard approach to the use of filters and practitioners should be cautious about using more than one filter in any post processing, in order that any phase shifts are kept uniform for all received waveforms.

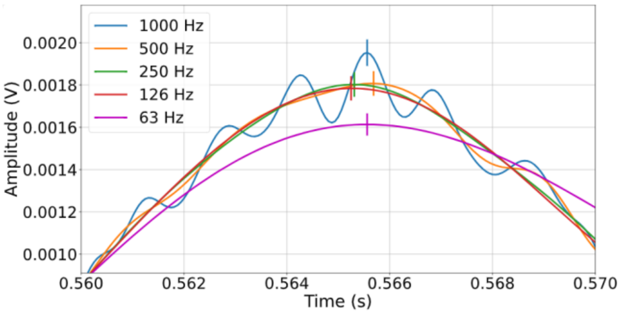

Figure 2. Example arrival time uncertainty due to frequency of filtering

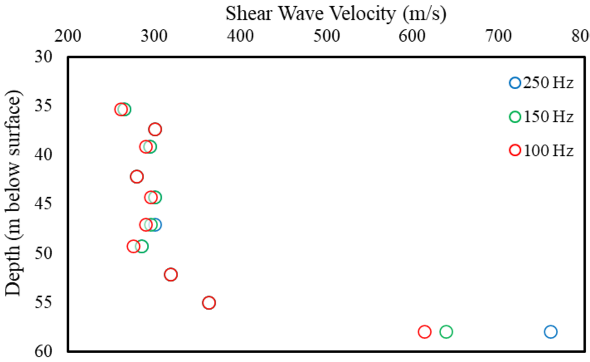

Figure 3. Variation in arrival time from example real world dataset using different filtering frequencies

In addition, the filtering process involves choosing the optimum cutoff frequency to discard the low frequency noises by high-pass/low-cut filter and high frequency noises by low-pass/high-cut filter from the raw signal. These filter functions depend on the cutoff frequency. Thus, selection of these cutoff frequencies require careful consideration as these may affect the resulting wave form by phase shift. Difference in phase shift can be observed by varying the cutoff frequency as shown in Figure 2. These phase shift result in variability in arrival time at different cut-off frequency. To illustrate this, shear wave velocities from a single real-world data set have been derived using various low pass filter frequencies and plotted in Figure 3. Here the error in v_s is between 0 and +/-2% with the deepest measurement being up to 7% error. Greater or lesser error could be experienced for different sites depending on the quality of the dataset. Further examination of more data sets to build up a picture of expected error across a site is not part of this work.

2.5. Source offset uncertainty

For the most common type of arrangement commercially, whereby the source is located on a separate skid offset from the centreline of the SCPT lance, accuracy of that offset distance measurement is important to reduce uncertainty. Masters et al 2023 explored using Straight Ray Analysis methods (ASTM D7400-17. 2019) a hypothetical scenario with source offsets between 2 and 10m with +/- 0.2m accuracy to model a worst case using conventional types of subsea positioning capability. Figure 4 illustrates these findings with most significant error in the shallow depths with small offsets and a reduction in error to less than 1% in all cases by 10m depth.

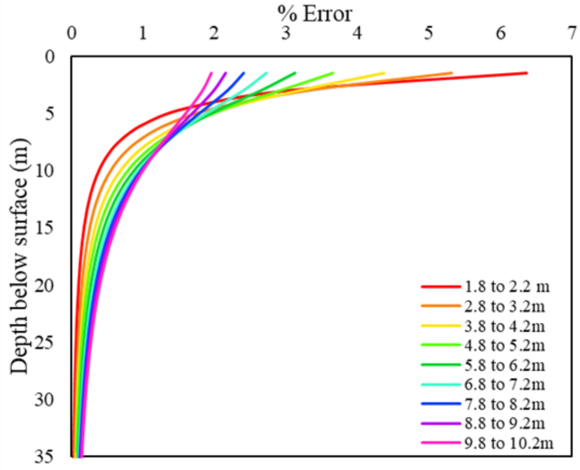

Figure 4. Error from source lateral offset inaccuracy of +/- 0.2m

Listed below is a series of hypotheses and assumptions about the effects on distance between active source and lance positioning, as well as the effects on the rotation of the source on a same axis; these assumptions have been part of the arrangement of trials performed onshore in a controlled environment where the uncertainty regarding distance measurement decreased and changes in the active source positioning were made with ease.

The assumptions and hypothesis are as follows:

1. Horizontal distance between the lance and the active source has an effect in the amplitude of the recorded signal due the energy of each shot and the damping of the material tested.
2. Rotation of the active source on a same axis shall imply an increment in the amplitude recorded. The nearest hammer provides the highest energy per shot in comparison to the farthest one, hence the distance of each hammer to the lance even in pseudo-perfect orthogonally positioning is important.
3. Positioning of the seismic lance has an effect on amplitude and polarity of recorded signals based on resonance due to closeness, rotation or inclination of the lance, hence the closeness, rotation and inclination are considered as important factors on amplitude and polarity of the recorded signals See Section 3.6 for a solution to this.
4. As it travels through the soil the amplitude of the seismic wave will decrease as a result of the energy absorption into the soil. Consequently, the recorded amplitude shall diminish as the radial offset of source is increased.
5. As the horizontal distance from seismic lance and source increases, the energy of the recorded signal will tend to be damped out simplifying the recording of the energy generated by S waves.
6. Near field effects will tend to increase as the horizontal distance between seismic lance and active source decreases due to the added complexity of wave propagation due increased anisotropy due to proximity in the source-lance system. This results a more complex waveform comprising a higher frequency content with a simultaneous reduction in the S-wave portion of the content and an increment in the P-wave content.
7. The hypotheses and assumptions listed above imply the following scenarios:

- There is an optimum distance between the active source and seismic lance, beyond which the near field effects will not be experienced.
- Sensitivity and type of sensors used are pivotal for the quality and accuracy of the recorded traces, hence for any type of sensor used the optimum distance source-lance is not fixed but is a range, meaning there is a maximum and minimum distance where the seismic traces can be recorded with the quality required for signal processing for geotechnical engineering purposes (deriving v_p, v_s to derive G_{max}).
- The maximum distance might imply a reduction in amplitude but possibly as well the recording of a waveform which is easier to process.
- The minimum distance might imply an increase in complexity of the signal recorded as well as an increase in the amplitude of the signal. In addition to near field effects, rod noise passing down drill the string or cone rods is accentuated. The more complex the signal becomes the higher is the cost of processing it.
- Incremental increases in waveform complexity result in incremental increases in processing uncertainty as the frequency content becomes more complex which generates different uncertainty factors such as those generated by filtering (Section 2.3) and anisotropy in P and S waves.

Trials performed offshore and onshore by the authors have demonstrated the effects of rotation of the active source on its axis, which have serious implications if the sensor arrays are not biaxial or triaxial (See Section 3.6). This reinforces the hypothesis of development of energy damping due hammer distance from the lance. These trials illustrated the different levels of asymmetry at the time of assessing the polarity in right and left hammers due the differences in amplitude and even slight differences in arrival times. Tests have been performed with measured rotations starting from orthogonal positioning. A full detailed account of the outcome of the trials is not part of this work.

2.6. Depth uncertainty

Uncertainty relating to depth of the receivers is an important consideration, particularly when operating in downhole mode where calculations including contributions from varying drill pipe lengths, stick up of those pipes above deck tidal corrections for water depth are made to establish borehole depth. For seabed mode, depth accuracy is likely to be much higher as long as rod slippage or excessive inclinations are avoided. For both seabed and downhole mode, sinkage of the SBF, or differential sinkage of a separate source compared to the SBF need to be assessed and alterations made to depths accordingly.

2.7. Soil Density uncertainty

Beyond the uncertainties associated with establishing reliable seismic velocities, for the engineer aiming to develop reliable G_{max} profiles to apply to design, use of appropriate soil densities is essential. Masters et al (2023) provide an hypothetical example of the effect on G_{max} from use of a series of perfectly plausible soil densities (between 1.9 and 2.05 Mg/m^3) as illustrated in Table 1.

Table 1. Example of error due to uncertainty in soil density

v_s (m/s)	Density (Mg/m3)	G_{max} (MPa)	Error (%)
100	1.90	19.0	3.8%
100	1.95	19.5	1.3%
100	2.00	20.0	-1.3%
100	2.05	20.5	-3.8%
	Average	19.75	

The authors recommend therefore that SCPT is not performed in isolation, but should be coupled where possible with high quality sampling of soils, with which to establish reliable soil density.

3. Calibration / verification / selection of SCPT equipment

To reduce uncertainty, SCPT must be planned rigorously. The equipment must be carefully selected, calibrated and verified to be operating correctly prior to deployment.

3.1. Trigger

Repeatability of the trigger and thus the repeatability of the sourcewave is very important, particularly when stacking of traces is required. Demonstration of trigger repeatability is essential during mobilisation. Testing systems which include the capability to view the trigger as a separate channel are advantageous in this respect.

It is the recommendation of the authors that where possible practitioners should include an ability to record the source wave close to the source itself, not just in the seismic lance, and to be able to display that signal on a dedicated channel which can be monitored during testing. It is the authors experience that the added layer of quality checking of the sourcewave using this arrangement can help enormously.

Conventional commercially manufactured systems normally record on x, y and z oriented sensors as either single or dual arrays, and record either 3 or 6 channels respectively. In this case, without making proprietary adjustments to the system this benefit is unlikely to be possible.

3.2. Seismic Lance

Performance and documentation of verification checks of the seismic lance should be performed onshore, away from the noise and vibration of the vessel environment. The authors recommend verification involving the use of apparatus which can generate measurable harmonic frequencies, calibrated with a suitably sensitive control accelerometer. This is essential not only to check that sensors are behaving as predicted, but to check that both sensor arrays in any dual array lance have identical response.

It's advisable to consider the importance of electronic components which form part of the acquisition system since this can be pivotal at the time of monitoring and preventing anomalies during the SCPT performance. If possible, it is recommended to run trials before deploying the lance and the active source and complement those tests with a trial once on the seafloor.

The aim of these trials must be to verify the integrity of the system; hence these tests should be comprised by the monitoring of noise levels (in decibels and voltage fluctuations) across the lance's geophones / accelerometers and active source (geophones / accelerometers and/or hydrophones) by means of testing the functionality of the seismograph and the performance of each channel to be used.

Noise variations should be thoroughly recorded into the operator's log and compared with the regular behavior of the geophones on deck and onshore in a more controlled environment (laboratory). In addition, the monitoring of voltage fluctuations is important to be registered since this could bring valuable data at the time of selecting the correct type of electrical components, isolators and for the filtering stage for signal processing.

During onshore laboratory testing, the authors have identified that certain types of AC to DC converters impose high frequency noises to the system, above 5kHz; this could be detected by the inspection of the frequency content of study traces by means of the Power Spectrum Density (PSD) method. This enforces the importance of performing noise monitoring during equipment mobilisation trials, ensuring adequate electrical grounding of the system and the importance of studying how the electrical connections might impact the acquisition time (system delay) and quality of the seismic signals.

3.3. Acquisition system

The system should be capable of recording the source waves at frequency high enough to remove the uncertainties outlined in Section 2.1 of this paper.

3.4. Lateral Offset

For arrangements where the source is deployed on a separate skid offset from the SBF, accurate measurement of the off-set between the source and the SBF is essential. Survey beacons mounted on the source and SBF can be used to provide 200mm accuracy. Other techniques can involve sonar imaging systems although they can pose their own challenges in poor environmental conditions. Options involving a 'Hard-tie' between the source and the SBF can be considered, but beyond the obvious deployment challenges, this solution may also suffer from increased noise transmission from SBF to the source. This would be particularly obvious in 'downhole mode' where noise can travel down the drill string from the vessel to the SBF.

3.5. Source Energy

Coupling between the source and the seafloor is essential to ensure transmission of the sourcewave into the underlying soil. The source should be heavy and with sufficient surface area to transfer the energy evenly. Skirts or channels are often included to increase the contact area. Deployment considerations are necessary however when considering adding weight and size to the source if the source is located on a separate skid.

Adjustment to hammer energy during fieldworks is advantageous. Whilst S and P waves can be measured at over 100m below sea floor where soil coupling is good, the soils are of low attenuation and the source energy is sufficient, for high attenuation soils such as stiff clays and where source energy is insufficient, measurements may become quite limited by 40 or 50m. In these cases, increasing hammer energy would be beneficial, despite the potential for extra hammer wear.

The inevitable requirement for stacking of multiple sourcewaves to recover useable data from deeper testing can require a great number of shots to be fired. These too have an implication on wear for mechanical systems and the wear itself can result in lower sourcewave quality. Thorough pre-checks of hammer components during mobilisation and the ability to replace worn parts easily during the field works between test locations is essential. Replacement of worn hammer components during testing is likely to result in aborting a location and having to bump over and test again. Particularly when attempting deep testing, practitioners should therefore weigh up the desire for many multiple shots at each depth against the risk of premature wear of the equipment and potential for reduced quality or even abortion of testing prematurely.

3.6. Triaxial Seismic system

The preference of the authors is for triaxial sensors. Use of these means that recorded seismic sourcewaves can be rotated onto the full waveform axis, which can increase the signal to noise ratio (SNR) and aid with interpretation of the incoming seismic wave.

It is the authors recommendation to perform wave quality characterisation techniques which include assessment of linearity. In depth analysis of triaxial sensor measurements can be made using Hodograms, Masters et al (2023). This means by plotting the x, y and z axis amplitudes against one another and using least squares best fit lines to assess linearity or rectilinearity values. Linearity values closest to 1 indicate highly correlated responses with high directionality and the full waveform should be considered reliable. Where low linearity values are achieved, this indicates lower SNR and resultingly poorer accuracy interval velocities are likely.

4. True Interval Straight Ray Analysis or Pseudo Interval (with True Ray Path) Analysis

There are two types of sensor configurations to determine an interval velocity profile:

- True-interval, which involves the simultaneous monitoring during each shot of dual sensor arrays offset vertically in the seismic lance, and the difference in arrival time is used to derive the wave velocity in the depth interval between the two sensor arrays.
- Pseudo-interval where a single seismic sensor array is advanced to various depths and the relative arrival time between depths is determined using separate seismic events. This may be performed with either single, or dual sensor arrangements.

True intervals analyses are performed using SRA (ASTM D7400-19). Pseudo Intervals analyses can be performed using SRA (in the same way as for True interval) or a True Ray Path / Ray Tracing approach.

Illustration of the potential differences between normalized velocities derived from a real-world data set for True Interval SRA and Pseudo Interval True Ray Path using Forward Modelling Downhole Simplex Method algorithm (FMDSM) after Baziw (2002) are presented in Figure 5 and Figure 6 respectively for a test where the seismic source was located on a separate skid. In both Figure 5 and 6, the v_s determined from SCPT is compared with to benchmark profile of v_s established empirically from PCPT data after Robertson (2009).

The most striking difference between the two methods is the markedly lower confidence in the velocities within the top 5 to 10m when using the True Interval SRA method. Masters et al (2023) provide a detailed summary of the advantages and disadvantages of the True Interval SRA and Pseudo Interval True Ray Path methods, along with recommendations for detailed post processing steps which may be taken to optimize quality of the derived seismic wave velocities.

5. Additional proposed processing methodologies

The different methods developed so far for the SCPT interpretation involve a thorough inspection and processing of the test's signals, nevertheless, it should be noted that the nature of geophysical surveys is that of indirect methods of measuring different properties of the near surface materials, whether it be seismic, electrical, gravimetric or electromagnetic.

Those methods are widely used in Geotechnical Engineering but to get a refined accuracy in results, and sometimes to select the proper interpretation method, they must be calibrated and aligned to physical direct measurements. Obvious direct measurements are the PCPT performed along the Seismic measurements.

Whilst 'blind' processing of seismic data sets is often practiced, avoiding artificially prejudicing processing decisions, the integration of stratigraphical information can be used to optimize processing.

Tip Resistance (qc), Sleeve Friction (fs) and Pore Pressure (u_{2}) from PCPT are directly correlated to the elastic behaviour of the materials investigated, and elastodynamics are precisely the main focus of SCPT and this application of signal processing.

With the above in mind, the next part of the process may be to identify the structure of each body wave (P and S), such as the phase velocity and group velocity for each layer or material encountered. The integration of this understanding may consider different assumptions and hypotheses such as the basic geophysical assumption that the phase velocity and group velocity are related in their structure with a dispersion effect in case of belonging to a same material (continuum), and also particular assumptions such as refraction and reflection effects that could be corrected in case of determining group phase properties.

If it is possible to correctly identify group phase properties per strata this can be used to correct the time displacement in seismic traces due the development of reflection or refraction effects when contrasts in elastic properties are found (from the stratigraphical layering from PCPT), taking as the correction factor the group arrival time of the body wave shared by the different traces of a same group. Such corrections based on group properties could be the basis to achieve a greater reliability for True Interval methods where True Ray Path or Ray Tracing methods are not available for the practitioner.

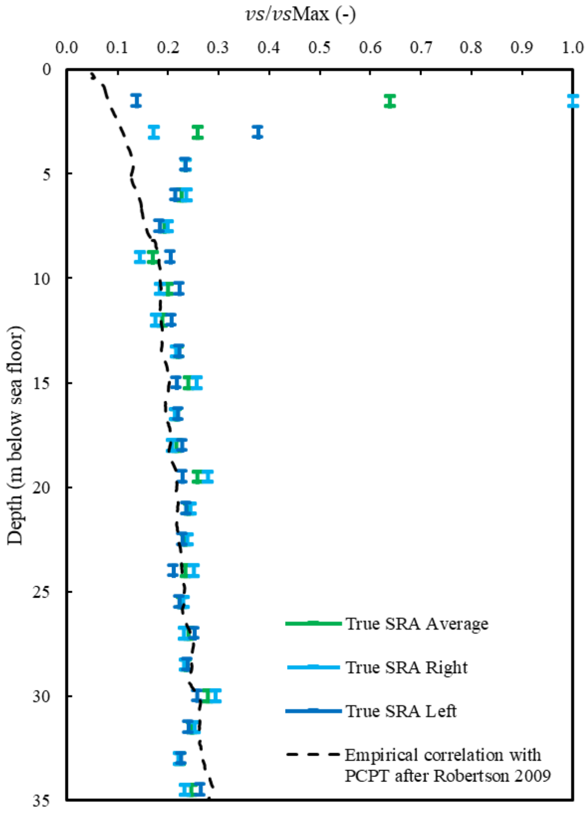

Figure 5. Normalised True Interval SRA analysis results compared to Robertson 2009.

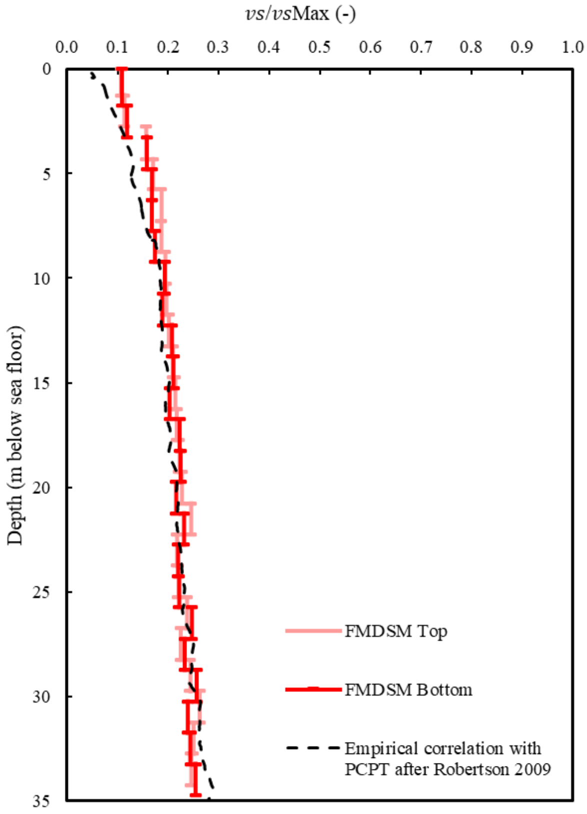

Figure 6. Normalised Pseudo Interval FMDSM analysis results compared to Robertson 2009. Same dataset used as in Figure 5

6. Conclusions and discussion

Section 2.1 highlights multiple significant sources of uncertainty, highlighting the need for great care when making determinations of time, distance and ultimately soil density. The various sources of uncertainty may all exist to a greater or lesser degree, leading to potentially poor seismic velocities if insufficient attention is paid to accurate measurement. One of the main purposes of this paper was to highlight these sources of uncertainty to help practitioners to minimise them in their own work.

Marine SCPT is still an evolving environment and lack of standardisation across the industry has led to multiple different systems and equipment arrangements being trialed and put into operation by multiple organisations, be they equipment spreads constructed by commercial manufacturers, or bespoke systems constructed by investigation contractors themselves. Section 3 provides guidance for practitioners planning work themselves on the different types of equipment suitable for use, along with the authors recommended procedures for preparation and operation. This information is equally valuable for those involved in the planning and specifying of SCPT.

There is also a lack of standardisation with regards to processing methodologies. In this paper True Interval Straight Ray approaches have been compared with Pseudo Interval True Ray path approaches. The distinct advantage of True Ray Path methods in shallow soils where the source is on a sperate skid are evident from the example velocity profiles. Masters et al (2023) provides a detailed comparison between the two techniques and also provides recommended guidelines for steps to take to validate the quality of the sourcewaves and apply necessary filtering and post processing prior to assessment of interval velocities. Additional procedures have been discussed in this paper for optimising the selection of appropriate seismic velocities based on integration of PCPT data into the post processing workflow.

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