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A comparison of shear wave velocity interpretation methods and application of a framework for quantification of uncertainty in marine seismic cone penetration testing.

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ABSTRACT: The seismic cone penetration test (SCPT) is a critical tool in the acquisition of in-situ shear wave velocity (V_s) and subsequent determination of Small Strain Shear Stiffness (G_{max}). Reliable and representative G_{max} profiles are considered of utmost importance in the design of offshore wind monopile foundations. Although seismic cone penetration testing measures shear wave travel times from a source to in-situ receivers along assumed travel paths to calculate V_s, there can be different sensor configurations implemented and analysis means used in such calculations, which inevitably, creates variations and uncertainty in these comparative determinations. As a result, there remains disagreement within the industry regarding the optimal data interpretation methods. This paper focuses on the comparison of V_s profiles generated via true interval and pseudo interval analysis methodologies, any differences that arise, as well as the potential implications and impacts on foundation design. Additionally, a framework to obtain uncertainty-quantified V_s profiles using a Bayesian inversion approach is applied. This inversion approach explicitly considers sources of measurement error which are generally neglected in order to deliver more realistic probability distributions of V_s. Further comparison and commentary are provided between the existing analysis methods and the new framework in context of robustness and validity.

Keywords: Seismic cone penetration test (SCPT); shear wave velocity (V_s); uncertainty quantification; Bayesian Inversion

1 INTRODUCTION

One of the most critical soil parameters for the design offshore wind turbine generator (WTG) monopile foundations is the small strain shear modulus, G_{max}.

At very small strain levels, it is not trivial to directly measure the deformation response of the soil. Therefore, G_{max} is usually derived indirectly from shear wave velocity (V_s) measurements incorporating bulk soil density (ρ), using Eq. (1).

$$G_{max} = \rho \cdot V_s^2 \qquad (1)$$

Within the context, accurate determination of V_s is paramount as the values are squared in the calculation of G_{max}.

While V_s can be estimated in the laboratory using bender element or resonant column tests, the results are strongly influenced by sample disturbance, sample preparation (particularly in cohesionless soils), assumed confining stress and uncertainty in the coefficient of earth pressure (K0), and initial void ratio. In situ tests are considered to provide more representative results, particularly in fractured soft rock and cohesionless materials where lab measurements are less representative of mass in situ response (e.g. Buckley et al, 2025). The benefit of in situ tests measurements in sand, for measurement and calibration of G_{max} with constitutive models, was highlighted by Taborda et al. (2020) by 3D FEA of monopile foundations compared to pile load tests. The V_s profiles can be obtained in the field using a range of techniques such as crosshole or downhole seismic; however, due to its cost effectiveness, speed of deployment and data quality the seismic cone penetration test (SCPT) is one of the most utilised in-situ methods for deriving the G_{max} of soil.

The marine SCPT methodology is well documented in the literature (e.g. Campanella and Davies, 1994, ASTM, 2019; ISO, 2023).

Although the methodology is generally standardised between most of the offshore systems, when it comes to hardware configurations, software interfaces, and methods of interpretation there can be significant differences.

It is reported in the literature that traditional SCPTs often produce scattered results of limited quality (Santos et al. 2023) and that the repeatability and reproducibility of offshore SCPTs are relatively low compared to onshore setups (Koreta et al. 2022).

Despite the uncertainties and complexities documented with SCPT acquisition results are often reported as a single deterministic data set without any measure of uncertainty that could be incorporated into any design process.

This paper presents the following:

a) Overview of a new novel SCPT system;
b) Presentation of data acquired at an offshore site located in the northern North Sea;
c) Comparison of the V_s profiles generated via true interval and pseudo interval;
d) Comparison of standard processing methodologies with application of a framework to obtain uncertainty-quantified V_s profiles using a Bayesian inversion approach. This inversion approach explicitly considers sources of measurement error so that a more realistic probability distributions of V_s can be delivered.

2 SCPT CONFIGURATION

2.1 Offshore Trials (2023)

In 2023 offshore trials were conducted on a novel marine seismic cone penetration testing system (Donaghy et al., 2024). The main objectives of the offshore SCPT trials were to a) test the system capabilities and performance including a qualitive assessment of the acquired data; and b) undertake a comparative assessment of the system capabilities and performance against existing systems and their respective acquired data.

2.1.1 Infinity SCPT

The SCPT system deployed in both the offshore trials and within the North Sea acquisition location considered within this paper is referred to as the 'Infinity Seismic Cone Penetration Testing System' (Infinity SCPT). The Infinity SCPT system was developed and launched in 2023. A detailed description of the system configuration and method of launch and recovery is described by Donaghy et al. (2024). A summary of the key components is provided in the following sections.

Figure 1. Infinity Seismic Cone Penetration Testing (SCPT) System

2.1.2 Seismic Source

The seismic source is mounted within the Infinity SCPT frame using a novel method that allows for both optimal ground coupling between source and seafloor, and mechanical decoupling of the source from the main seabed frame, whilst maintaining a constant offset.

A variable ballast system ensures that seismic energy is effectively transferred into the soils. The horizontal offset (at the seafloor) between the seismic source and the vertical axis of the rod string is fixed at 1.41m as shown in Figure 2.

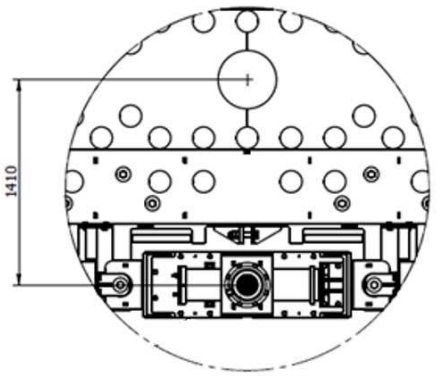

Figure 2. Schematic of seismic source depicting offset from seismic point source to SCPT rod axis.

The seismic source is deployed to the seafloor coupled to the Infinity SCPT and comprises two electro-mechanical hammers mounted in opposing directions (Left and Right, or L and R), which are used to generate horizontally polarised vertically

propagating shear (SH) waves. A third hammer is mounted vertically and is used to generate compression (P) waves, which are omnidirectional.

The seismic acquisition modules are mounted on the bottom end of a CPT push rod string, which is coiled on a storage drum mounted inside the pushing apparatus of the Infinity SCPT.

2.1.3 Seismic Array

The seismic array, mounted behind a conventional piezocone penetrometer comprises a pair of tri-component accelerometer-based sensors. These dual array seismic receivers are mounted at 530 mm and 1030 mm above the cone tip, giving a vertical separation of 500 mm. Each array is mounted orthogonally (X, Y and Z components), with the Y axis in co-alignment with the two horizontal seismic hammers (L and R), as presented in Figure 3.

Utilising such configuration of seismic source with seismic array allows for evaluation of SH velocity through comparison of the phase, or time difference between shear waves for all sensors i.e. pseudo-interval, or for upper and lower sensors i.e. true interval.

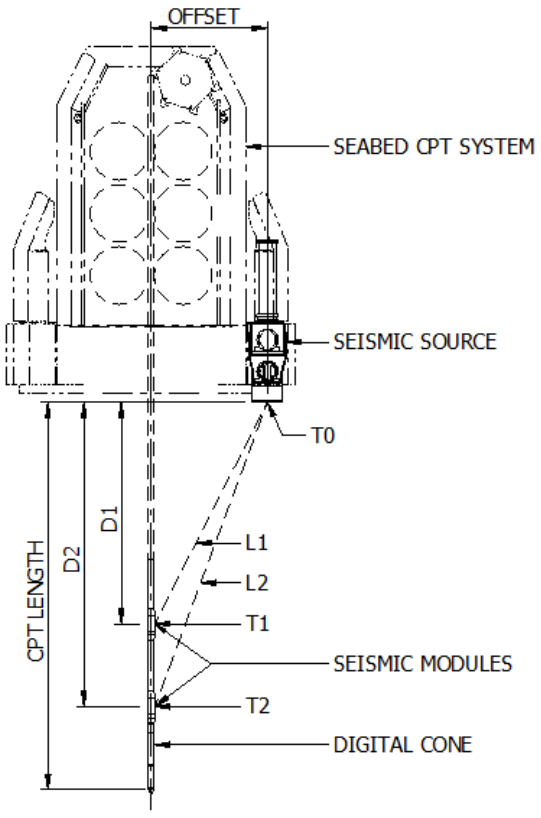

Figure 3. Schematic of Infinity SCPT acquisition setup. (Credit: A.P. van den Berg).

2.1.4 Seismic data and processing

At each test interval, 3 non-polarised shot repetitions were performed on each hammer. The raw dataset for each location comprises a collection of raw signal traces (X, Y, and Z components all included), each corresponding to a single shot labelled with receiver depth, source horizontal offset (constant for each location), and sampling rate (0.2 ms for all cases considered).

Details of the seismic acquisition engineering considerations are provided by Donaghy et al., 2024 and further explanation of the data acquisition and processing is described by Christian et al., 2025.

3 TESTING

The data used in this analysis was acquired within a commercial project at an offshore site located in a northern region of the North Sea, accumulating approximately 700 m of SCPT pushes and acquiring vs measurements from 4200 seismic shots. Within this project, both pseudo and true interval analyses were undertaken.

All locations showed similar conclusion, however, for the purpose of and brevity of this paper detailed results are only presented for one representative location.

3.1 Site Conditions

The site lies within a region of the North Sea whose Quaternary geological sequence is represented by repeated phases of erosion and deposition associated with the Pleistocene glaciations. (Gatliff et al. 1994).

Table 1. Representative Location - Engineering geological soil description.

Soil Description	From (m BSB)	To (m BSB)*
Loose to medium dense silty SAND with thin to medium spaced thin to medium beds of very-loose to loose sandy silt	0.0	4.3
Soft to firm silty CLAY	4.3	7.2
Firm to stiff silty CLAY with medium spaced thin to medium beds of loose sandy silt.	7.2	14.5
Firm to stiff silty CLAY	14.5	16.5
Very dense silty SAND and GRAVEL.	16.5	16.9

* Depth in m below seabed (m BSB)

This period has left a heavily channelled sequence of glacial and glacio-marine sediments overlain by softer late glacial and Holocene Units.

The general Quaternary geology of the project location comprises:

- Marr Bank Formation;
- Wee Bankie Formation;
- Forth Formation;
- Coal Pit Formation;
- Aberdeen Ground Formation.

At the selected representative SCPT location, the encountered conditions are described in Table 1.

4 RESULTS, ANALYSIS AND DISCUSSION

4.1 Data review and evaluation

When assessing the quality of the V_s data, it is acknowledged that no agreed standard for quantitative measure of accuracy exists. As mentioned, V_s results are often reported as a single deterministic data set without any measure of
uncertainty that could be incorporated into any design process.

Therefore, in order to demonstrate acquisition system efficacy and reliability, a high degree of confidence in the results should be demonstrated. For this purpose, the calculated V_s profiles were compared to a) existing data acquired at the same location, b) established correlations – non site specific, and c) new correlations – site specific.

At this project location, no previously acquired data existed for comparison and, to date, no new site specific correlations have been developed. Therefore for a measure of system efficacy and reliability we assessed the acquired data by analysing it in a true interval and pseudo interval methodology and comparing both outcomes. In addition we compared against publised V_s – CPT correlations.

Out of ten published correlations between V_s and CPT data analysed, Roberston (2009) proved to be the best fit against the acquired data, thus providing a benchmark for assessing the data set.

Roberston (2009) is a general CPT- V_s correlation based on 1035 data pairs from Holocene and Pleistocene soil sites.

4.2 Comparison

True interval analysis involves the simultaneous measuring of shot arrivals, or seismic events, on a dual sensor seismic array, the difference in arrival time between two pairs of sensors at one depth interval is used calculate V_s. Pseudo-interval analysis involves the advancement of the seismic array to various depths and measuring the difference in the relative arrival times between depth intervals using separate seismic events to calculate V_s. This may be performed with either single or dual sensor arrangements.

A comparative assessment between the data analysed in both True and Pseudo analyses methodologies demonstrate a strong comparison, with similar velocity profiles and trends with depth. The calculated V_s for this selected location is presented in Figure 4.

Good agreement is found between the derived V_s from the SCPT and the estimated V_s from Robertson (2009), however, there is a consistent underestimation of V_s using this correlation.

These positive agreements further confirm the reliability of the newly developed systems presented in this paper.

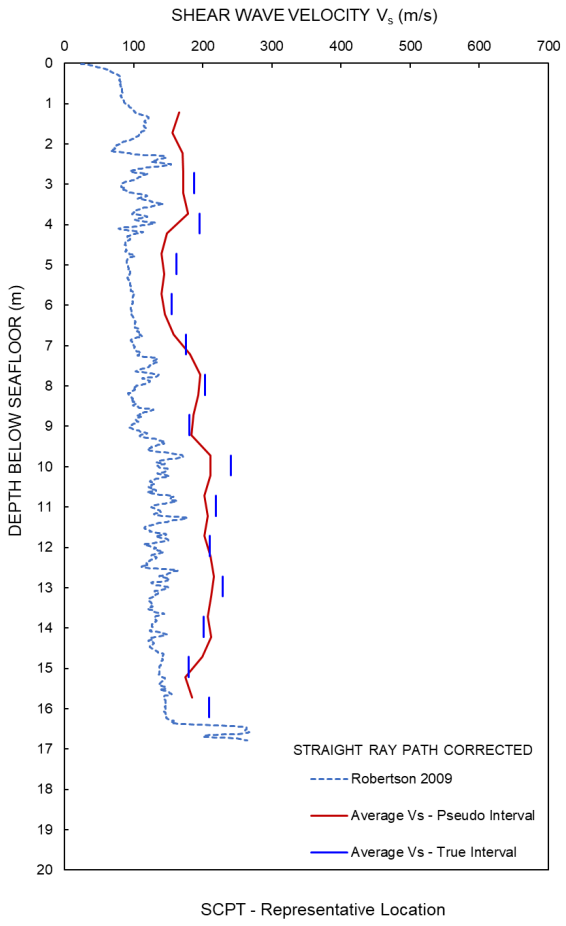

Figure 4. V_s measurements from example SCPT

As discussed in the introduction, these results are often reported to end users as a single deterministic data set without a measure of uncertainty that can be

considered within the design process. In the following section we will look further into the measurement of the associated uncertainty and assess the reliability of the acquired data and system capability within this context.

4.3 Quantification of uncertainty

The data for SCPT has been interpreted using two methods: (i) a standard interval approach, and (ii) the Bayesian inversion approach proposed by Zheng et al. (2024a, 2024b). For both methods, all seismic traces were pre-processed using the following techniques:

- 150 Hz low-pass filters were applied to reduce external noise;
- 50 ms Hanning windows (starting just prior to the arrival of each signal) were applied to isolate the arrival peaks and reduce residual oscillation, improving the accuracy of cross-correlation based travel time picking;
- Up-sampling was applied to increase the sample rate from 0.2 ms to 0.1 ms, improving the precision of the travel time picking;
- Left and right polarised traces were unified by inverting all right-polarised traces.

4.3.1 Standard Interval Approach

The interval approach considers the stacked signals (i.e., sum of all recorded seismic shots) at pairs of adjacent geophones, and estimates V_s assuming straight ray paths between the source and each geophone:

$$V_s = \frac{L_{i+1} - L_i}{t_{i,i+1}} \tag{2}$$

where L_i, L_{i+1} represent the ray path lengths from source to each geophone, and $t_{i,\,i+1}$ is the relative travel time between the geophones, herein derived via the cross-correlation approach (see e.g., Baziw, 1993), which cross-correlates the two stacked signals and identifies the shift at which maximum correlation occurs.

The above calculation has been performed for every pair of adjacent geophones – this includes both true-interval (TI) pairs, comprising the top and bottom geophones at a single probe depth, and pseudo-interval (PI) pairs, comprising the bottom geophone at a given probe depth and the top geophone at the subsequent probe depth.

For the example SCPT dataset, the probe was progressed 1 m for each test, which, combined with the 0.5 m accelerometer spacing within the probe, results in all TI and PI intervals spanning 0.5 m. The results are shown in Figure 5. A clear profile is observed with minimal scatter, and strong agreement between the TI and PI values can be seen. These factors are indicative of a high-quality acquisition procedure.

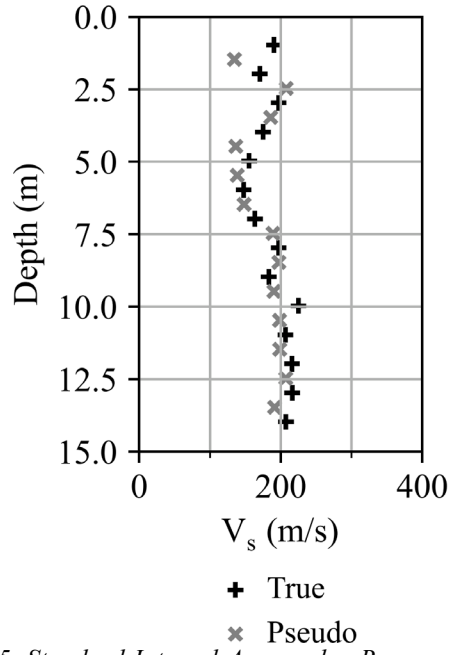

Figure 5. Standard Interval Approach - Reprocessed data utilising 50ms Hanning Windows, Up-sampling and unification of left and right polarised traces

4.3.2 Bayesian Inversion Approach

The Bayesian inversion approach, described by Zheng et al. (2024), is able to deliver probabilistic profiles of V_s as well as estimates of key measurement errors during acquisition. The approach considers the full dataset of individual (i.e., unstacked) seismic traces, which may exhibit natural variance between equivalent travel times and/or inconsistencies in the data acquired by different geophones. The method propagates the natural variance in travel time through to V_s via a curved ray path velocity model, delivering the V_s profile as well as its associated uncertainty, and is able to account for inconsistencies in the data via the introduction of two measurement error terms. ε_t represents the error in TI comparisons due to inconsistencies in the timing and/or signal characteristics of the top and bottom geophone recordings. ε_p represents the errors in PI comparisons due to timing, depth, or any other inaccuracies which cause discrepancies in apparent travel times between different probe positions.

The analysis has been run using prior standard deviations of 0.1 ms and 0.2 ms for ε_t and ε_p, respectively – the derived profiles for V_s and for the error terms are shown in Figure 6.

The uncertainty bounds in V_s (which reflect the uncertainty during acquisition) are relatively narrow

and the general profile follows that of the interval method closely. The estimated errors are also very low, which is consistent given the high level of compatibility between TI and PI measurements observed within Figure 5.

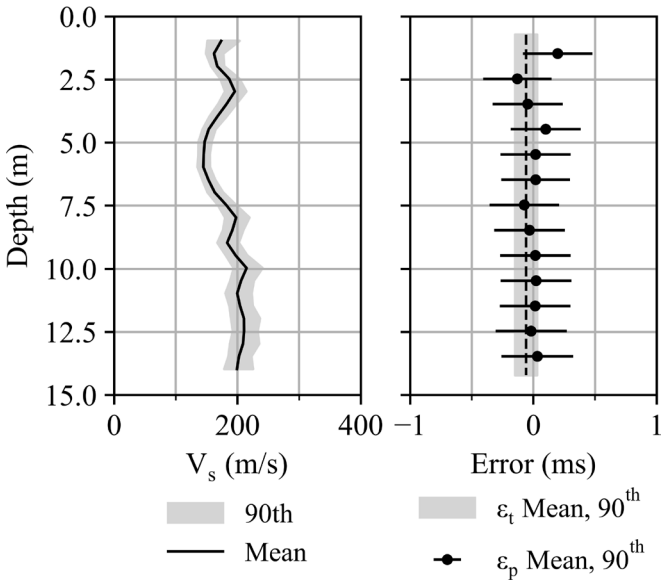

Figure 6. Bayesian Inversion Approach - ε_t represents the error in TI comparisons due to inconsistencies, and ε_p represents the errors in PI comparisons due to timing, depth, or any other inaccuracies.

The mean (i.e., most likely) value of ε_t is estimated as 0.06 ms and the average mean value of ε_p throughout the profile is 0.05 ms.

For reference, the method was also used to interpret over 100 publicly available seabed SCPT datasets across several wind farm sites in the Dutch sector (from RVO: https://offshorewind.rvo.nl/), and the average mean ε_t across all locations was found to be 0.17 ms (Zheng et al. 2024a, 2024b). The average mean ε_p was found to be 0.30 ms, although this cannot be compared directly, since a different prior standard deviation of 0.4 ms was used. Regardless, these reference values from an already established SCPT acquisition system demonstrate that the newly proposed technology is capable of performing to a high, industry-acceptable standard.

5 CONCLUSIONS

Application of the proposed Baysian inversion approach provides the end user with valuable information on the reliability of the provided data, and thus the relaibility of the acquisition system, through estimation of measurement errors directly. Classic processing and interpretation methods ignore such errors and may sometimes deliver innacuate results.

As the industry reports that the traditional SCPT methods often produce deterministic data of perceived limited quality, the authors suggest the importance of implementing such a framework for the quantification of uncertainty as standard with each supplied data set; demonstrating that the results can be relied upon and are fit for their end purpose.

AUTHOR CONTRIBUTION STATEMENT

D. Donaghy: Data curation, Conceptualization Analysis, Writing- Original draft. **T. Zheng**.: Formal Detailed Bayesian Analysis, Software Script, Bayesian Methodology **R.M. Buckley, S. Whyte, H.A. Christian**: Reviewing and Editing.

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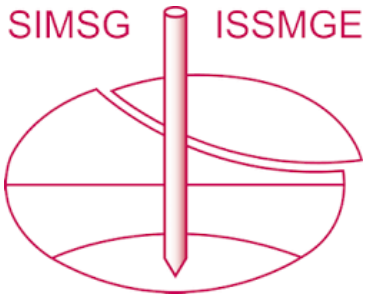

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