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Assessment of seismic cone penetration tests: equipment set up, processing and interpretation workflows. Field test study

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ABSTRACT: The seismic cone penetration test (SCPT) is a key *in situ* method for determining small strain shear modulus (G_{max}), essential for optimizing offshore wind turbine foundation design. However, SCPT data from different systems often show significant scatter, which increases design uncertainty preventing optimal design. This study compares SCPT data from three contractors at two offshore sites to identify the most effective system configurations, data processing, and interpretation workflows. Results highlight the limitations of existing standards in ensuring reproducibility and consistency. Recommendations are provided to improve SCPT acquisition, data processing, and interpretation, aiming to enhance the reliability of G_{max} estimations for geotechnical applications.

Keywords: small strain shear modulus; SCPT; uncertainty analysis; processing and intepretation; offshore wind, foundation

1 INTRODUCTION

Understanding the uncertainties associated with measuring the small strain shear modulus (G_{max}) is essential for geotechnical design, particularly for laterally loaded offshore wind turbine foundations. Reducing uncertainty in G_{max} estimations can improve soil stiffness assessments, leading to optimized monopile foundation design. G_{max}, derived from shear wave velocity (V_s) and soil density (ρ) measurements, is highly sensitive to uncertainties in V_s due to the squaring of V_s in the calculation (see equation 1).

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

SCPT is a widely used *in situ* method for determining V_s offshore. However, offshore SCPT data often exhibit considerable scatter and limited Reproducibility, increasing the uncertainty in G_{max} determinations (Gibbs et al., 2018; Masters et al., 2019; Koreta et al., 2022). Although standards such as ISO 19901-8 (2023) and ASTM D7400 (2019) provide guidance on SCPT methods, they offer limited support for managing uncertainty and interpreting data.

Ørsted conducted a comparative study of SCPT configurations at two North Sea sites with distinct soil profiles, where three contractors each performed three tests to assess SCPT seafloor mode methodologies.

In this paper, recommendations are given for SCPT data acquisition, processing, and interpretation to enhance the reliability of G_{max} determinations in offshore applications.

2 SITE CONDITIONS

Two locations, herein referred to as Cluster 1 and 2 were selected for trials. At each cluster, three contractors (referred to as Contractor A, B and C) performed three SCPTs to a target depth of 25 meters below seafloor (bsf). The SCPT data were collected within a 5 m radius of a central borehole, as shown in Figure 1. The two clusters exhibit distinct soil characteristics as shown from the corrected cone resistance (q_T) results in Figure 2.

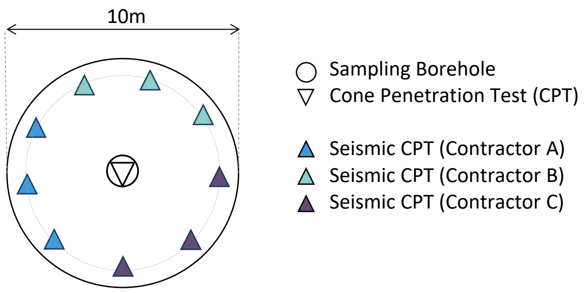

Figure 1. Schematic illustration of the testing program conducted at Cluster 1 and 2.

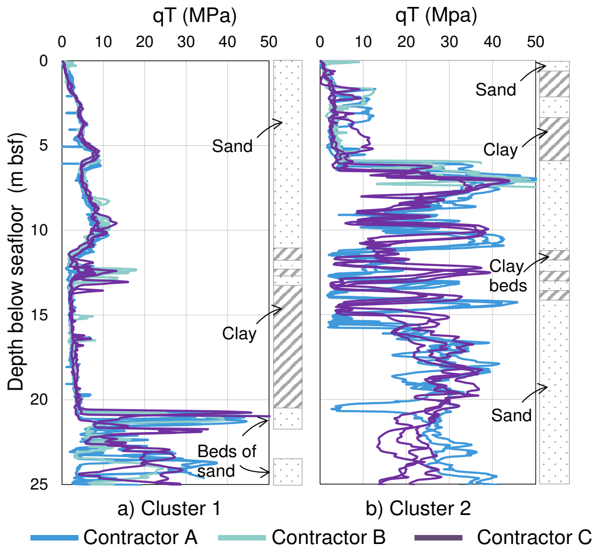

Figure 2. Corrected cone resistance results from all contractors at a) Cluster and b) Cluster 2.

Cluster 1 has an 11 m thick sand layer over a 10 m thick, high-strength clay layer. Underlaying, the profile is interbedded with clays and thin to thick widely spaced sand beds.

Cluster 2 has a more varied profile, starting with a 1 m thick loose sand layer, followed by a 5 m thick high-strength clay layer, locally interbedded with thin sand beds. This is underlain by a medium to very dense sand unit with closely spaced thin clay beds that continues to about 25 m bsf.

3 ACQUISITION SETUP AND OBSERVATIONS ON SIGNAL QUALITY

The three contractors employed distinct dual-receiver setups to enable true-time interval velocity measurements, each employing custom-built seafloor mode configurations and unique seismic sources (hammer types) to generate shear waves in two opposite directions. More details on the acquisition setup and observations on the quality of the first arrivals are provided in Table 1.

Table 1. SCPT acquisition set up parameters for each contractor.

Figure 3 shows a comparison between the characteristic signals associated with each contractor at Cluster 1.

3.1 Quality Assessment

The quality of the raw seismic datasets is assessed using key statistical metrics: signal-to-noise ratio (SNR), correlation coefficient (R^2), standard deviation, and expanded Type A uncertainty evaluated over repeated tests. SNR, a primary measure of data quality, is defined as the ratio of the average signal power ($\bar{P}_s$) to average noise power ($\bar{P}_n$) in decibels, where noise levels are determined from the pre-recording time interval.

$$SNR = 10\log_{10}(\bar{P}_s) - 10\log_{10}(\bar{P}_n) \quad (1)$$

Average SNR for each individual shot values ranged from 10–13 dB for Contractors A and B, and 29–31 dB for Contractor C. The difference in SNR is visible in raw time sections (Figure 3), with studies (Soage Santos et al., 2022) indicating that SNR values below 30 dB significantly increase V_s uncertainty due to noise interference during signal trace cross-correlation.

Signal reproducibility was assessed using trace cross-correlations, providing both time variation (Δt), presented in Figure 5a, and R^2 between repeated recordings at a single receiver or between receiver pairs (shot gathers). This repeatability analysis was performed at 5, 10, and 15 m depths, where each contractor conducted an additional 10 shots. R^2 values for receiver pairs range from 0.73 to 0.98, and for individual receivers from 0.72 to 0.96, indicating consistent receiver alignment and response. The standard deviation of Δt for receiver pairs ranges from ±0.03 to ±0.17 ms, while for individual receivers, it is ±0.68 to ±2.16 ms.

The higher Δt standard deviation for individual receivers is attributed to trigger timing inaccuracies, observed across contractors, though this does not affect receiver pairs as analysis is strictly performed in the pre-stack domain. Thus, further analysis will focus exclusively on receiver pairs. The maximum Δt standard deviation for receiver pairs (±0.17 ms) corresponds to a derived V_s range of 230 to 273 m/s (–8% to +9%) assuming a 250 m/s actual soil velocity, using a dual receiver setup with a 0.5 m spacing. Such uncertainties are substantial and contribute to errors in G_{max} calculations.

Contractor	A	B	C
Vertical receiver spacing [m]	0.5	1	0.5
Receiver components	X, Y	X, Y, Z	X, Y, Z
Receiver type	Accelerometer	Geophone	Accelerometer
Recording frequency [kHz]	5	40	10.42
Upscaling frequency [kHz]	40	40	40
Pre-recording time [ms]	50	20	46
Recording time length [ms]	600	400	1000
Source type	Hammer	Hammer	Hammer
Source deployment	Decoupled from seabed frame	Decoupled from seabed frame	Mechanically coupled to seabed frame
Shot direction	Left & Right	Left & Right	Left & Right
Number of shots per depth and shot direction	5	5	5
Range horizontal offset between source & receivers [m]	2.9-4.3	4.7 and 4.8	0.82 and 0.64
Filtering during acquisition [Hz]	No	No	1250
Dominant frequency [Hz]	28.6	42.2	42.9
Noise peaks [Hz]	130; 200-300	>400	600
Observations on V_s arrival	Clear one-cycle Ricker wavelet; early arrival; recoil ~120 ms after; noise from 15 m.	Clear but weak, masked by higher velocity phase; similar to A; noise from 18 m.	Clear oscillating signal with long decay; unique waveform

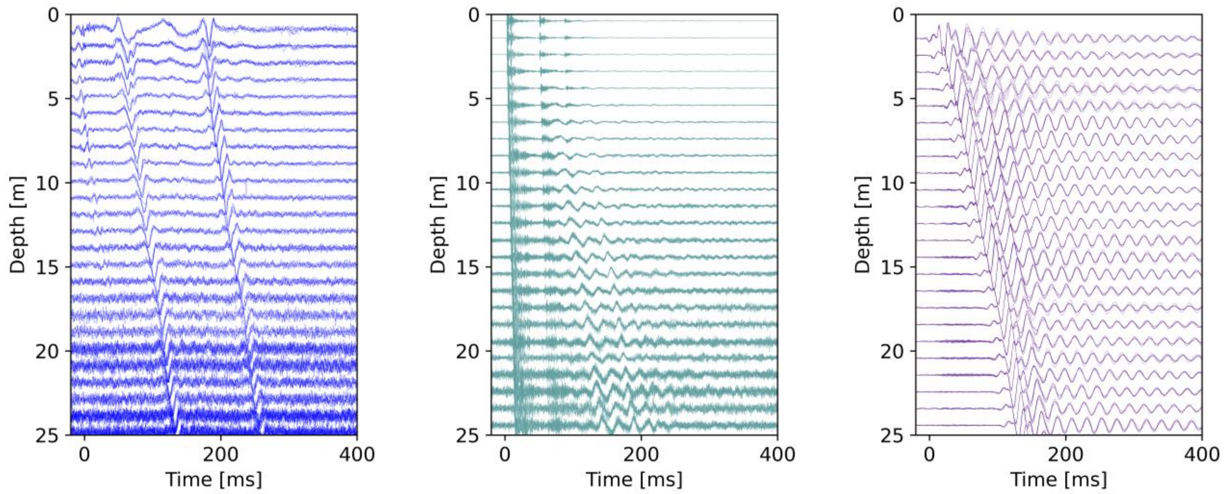

Figure 3. Examples of characteristic signals from each contractor at Cluster 1

3.2 Assessment of Reported Shear Wave Velocities

Each contractor applied distinct signal conditioning, processing, and interpretation workflows to estimate V_s from the seismic data. The resulting V_s values, shown in Figure 4 exhibit significant scatter both between contractors and across repeated tests by the same contractor, particularly at shallow depths (less than 10 meters), where discrepancies exceed 100%. Given the minimal variability in q_T results shown in Figure 2, the observed variability in V_s cannot be attributed to soil differences.

The scatter in V_s estimates is most pronounced at shallow depths for contractors using larger horizontal offsets between source and receivers and at greater depths (>20m) where SNR decreases dramatically.

Figure 5b illustrates the variation in V_s estimates provided by each contractor's preferred workflows. The observed variability is notably higher than the reproducibility results presented in Figure 5a, underscoring the importance of selecting appropriate procedures for signal pre-conditioning, processing, and interpretation to reduce overall uncertainty.

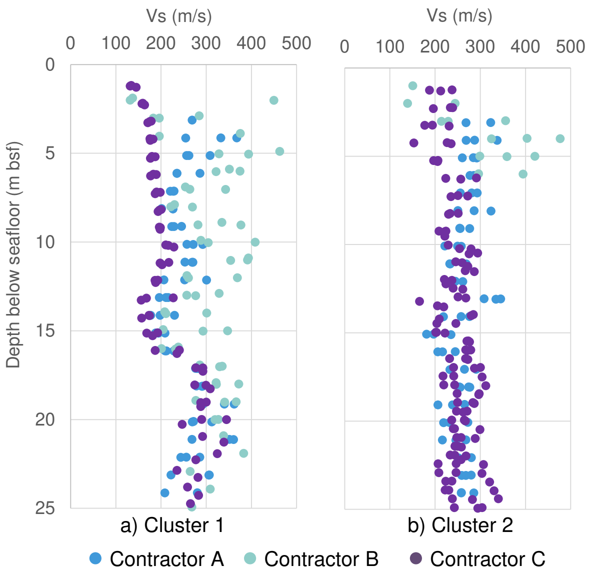

Figure 4. Reported Vs estimates for each contractor at Cluster 1 (a) and Cluster 2 (b).

4 PROCESSING AND INTERPRETATION PROCEDURE

To understand the impact of processing and interpretation procedures all signals were subjected to a unified, robust and automated processing and interpretation procedure consisting of five main steps. Further details for each step of the procedure are provided in Table 2.

5 DISCUSSION

Figure 6 shows V_s estimates obtained from a unified data processing workflow, presented in Table 2, comparing three interpretation methods. True-time and pseudo-time interpretations assuming straight travel paths, were found unsuitable with large horizontal offsets. The slope method significantly reduced V_s uncertainty within and across contractors. Although ray path and travel time inversion techniques (e.g., Stolte & Cox, 2020, Wang 2021) were not utilized in the analysis presented here, further assessments by the authors indicate that incorporating these methods could reduce uncertainties further.

The unified workflow emphasizes the importance of quality control, standardized pre-conditioning, and suitable filter selection. A notable reduction in R^2 after trace processing brought contractor results closer together, underscoring the workflow's ability to harmonize data across varied setups. Signal stacking was excluded from the workflow due to its lack of improvement in V_s estimates; instead, expressing V_s as the mean with expanded uncertainty provides a clearer measure of result variability.

Current industry practice commonly assumes that Vs estimations can achieve uncertainty levels below 10%. However, as demonstrated in Figure 5a, this presumed threshold of uncertainty is already met or exceeded by the inherent reproducibility of raw measurement data itself. Furthermore, this initial uncertainty is compounded significantly throughout subsequent stages of data processing and interpretation. Even when applying a standardized, unified processing method, Figure 6c clearly illustrates that uncertainty remains notably high, with substantial scatter evident across Vs estimates at similar depths. Given that uncertainty only increases with each processing step, it is essential to address the initial measurement uncertainty by enhancing equipment precision standards. Implementing stricter equipment regulations and improved calibration protocols is thus critical for minimizing uncertainty and achieving reliable and accurate Vs estimations.

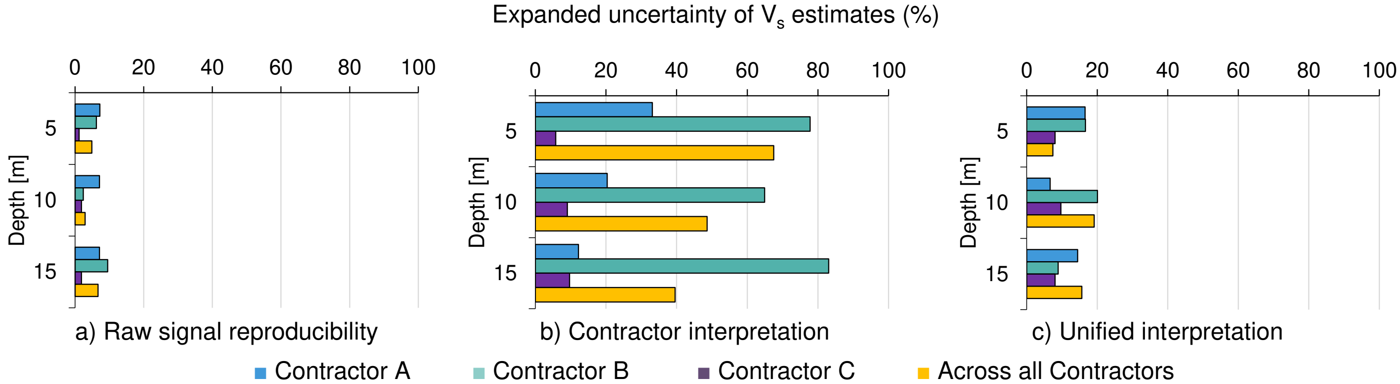

Figure 5. Expanded Standard Uncertainty (k=2) for determinations of Vs for the next cases: a) Signal reproducibility associated to raw signals calculated using the observed time lag variations over consecutive shots at each depth related to a reduction velocity of 200 m/s; b) Contractors' interpretation Vs estimates over repeated locations and c) Unified interpretation Vs estimates over repeated locations.

Table 2. Unified workflow for data processing and interpretation

Stage	Description	Aim
Signal pre-conditioning	1. Upscale trace sampling rate to 40kHz 2. Standardize trace header data from contractors 3. Adjust amplitude offsets for reliable quantitative analysis 4. Create shot gathers	Prepare traces for quality control. Adjust amplitude offsets for reliable quantitative analysis.
Quality control	5. Visual inspection of signals 6. SNR analysis 7. Reproducibility analysis	Eliminate incorrect or erroneous signal from analysis. Quantify uncertainties from Reproducibility.
Trace-processing	8. Fast Fourier Transform (FFT) analysis is applied to investigate the frequency content of all traces for the full time series. 9. Application of conservative Butterworth low pass filters to avoid distorting the signal of interest. Cut-off must be greater than twice the dominant frequency of the shear wave. 10. Repeat quality control with filtered signals	Eliminate undesired noise or other unwanted features and precondition signals for further analysis.
Determination of Time-lag	11. Perform cross correlation analysis to determine R^2 and Δt between receiver pairs and SNR at each receiver depth level. 12. A time window can be applied around the first arrival.	Determine representative Δt, R^2 and SNR profiles as a function of depth.
Interpretation	13. Apply appropriate interpretation methods such as; a) Slope method (Stolte and Cox, 2020) b) Modified ray-path (Wang 2021) c) Travel Time Inversion For this paper, method a was used.	Convert Δt into V_s estimates. For large horizontal source-receiver offsets (>1m), travel time reduction methods (a) or accurate ray-path methods (d or e) must be applied. For small horizontal source-receiver offsets (<1m) the True-time method can be applied in a dual setup (a) and Pseudo-time (b) in a one receiver setup.

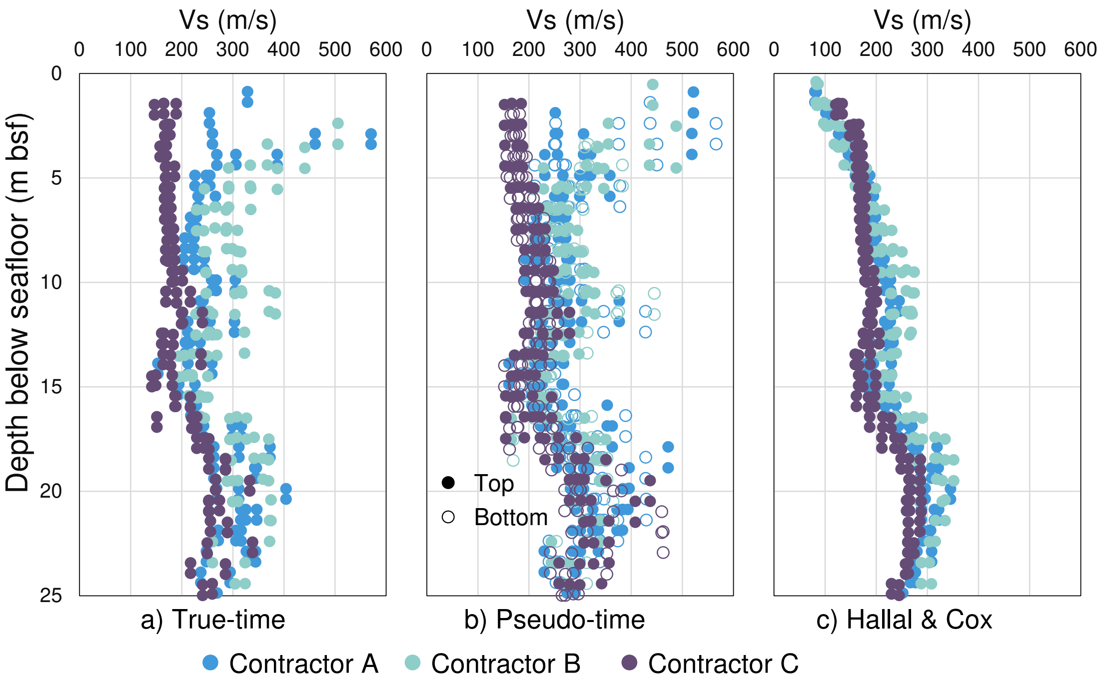

Figure 6. Interpretation of shear wave velocity using the unified workflow

6 CONCLUSIONS

This study highlights the need for targeted improvements to reduce the high uncertainty in shear wave velocity (V_s) determinations from offshore SCPT tests. These improvements fall into two main categories:

1) **Equipment-Related Improvements**
   - **Enhanced Reproducibility:** Consistent and reliable V_s measurements require improved reproducibility through robust methodologies and stricter calibration requirements for triggering devices and sensor synchronization. Standarised calibration protocols and real-time synchronization monitoring could help standardize results.
   - **Increased Signal-to-Noise Ratio (SNR):** Increasing SNR, particularly below 20 meters, is critical to reducing uncertainty in V_s estimates.
2) **Processing and Interpretation Improvements**
   - **Unified Workflow:** A standardized data processing workflow effectively minimized V_s variability across contractors. The slope method proved beneficial, and further application of ray tracing techniques is recommended to reduce uncertainties even further.
   - **Consistent Pre-Conditioning, Quality Control, and Uncertainty Reporting:** Standardized pre-conditioning and rigorous quality control steps, such as filtering and cross-correlation assessments, improved alignment across contractor's results highlighting the need for uniform processing practices. While improvements were achieved, significant V_s uncertainty persists, reaching 19% at 10 meters depth, which translates into Gmax discrepancies of up to 77% between contractors. Reporting Vs estimates with expanded uncertainty is recommended to provide a clear representation of measurement reliability.

The findings of this study clearly indicate that the site investigation industry must prioritize the standardization of both SCPT equipment and data processing and interpretation methods. Enhanced standardization will reduce inter-contractor variability, ensuring reliable and consistent V_s and G_{max} values essential for offshore geotechnical design.

AUTHOR CONTRIBUTION STATEMENT

R Soage Santos: Concept, Analysis, Writing. **K. Lundvig**: Method, Software, Analysis. **J. Park, G. Sauvin, O. Koreta**: Investigation, Analysis, Writing-Reviewing and Editing.

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