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A case study addressing the development of a novel marine seismic cone penetration testing system.

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ABSTRACT

Within the offshore wind sector, following the conclusions of the Pile Soil Analysis (PISA) Project increased emphasis has been placed on the acquisition of in-situ G_{max} data, to corroborate laboratory-based measurements, to allow for foundation weight optimization. This requirement for higher fidelity data at all wind turbine locations is coupled with the increased requirement to acquire data in shorter periods to meet ambitious development schedules for offshore wind farms. The development of a deep push seabed SCPT which can be deployed fully autonomously is considered to address this challenge facing the offshore wind industry.

Recognising that within the current standards there is a shortfall on what is considered as accurate and reliable data with regards to having confidence in the shear wave velocity (v_s) measurements obtained offshore, there is a requirement for discussion within the industry; clients, designers and contractors, on how to provide improved set-ups, acquisition and interpretation methods in order to increase the confidence in the v_s data acquired.

The case study described within this paper, initiated by such dialog, presents the specification, construction, testing and utilisation of a dual array non-drilling mode seismic cone penetration test (SCPT) device and seismic source to provide demonstrable reliability and accuracy in acquisition and interpretation of in-situ v_s measurements.

Within this context, the paper describes; the engineering considerations and optimisation of a novel device intended for deployment from a new generation of robotic vessel; application and limitations of the set-up during trials and offshore operations; commentary on the in-situ data including challenges encountered during interpretation and comparison with existing data acquired at the same location, established correlations and site-specific correlations.

Keywords: ISC7; seismic CPT; in-situ testing; shear wave velocity (v_s); shear modulus (G_{max}).

1. Introduction

The small strain stiffness (G_{max}) is a fundamental parameter for the design of offshore wind turbine foundations, particularly monopiles, given its importance for the structural natural frequency. At very small strain levels, it is not trivial to directly measure the deformation response of the soil. Therefore, it is usually derived indirectly from shear wave velocity (v_s) measurements incorporating bulk soil density (ρ), using Eq. (1).

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

Due to its cost effectiveness, speed of deployment and data quality the seismic cone penetration test (SCPT) is one of the most commonly 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. The main differences between the offshore systems encountered are the:

a) source characteristics (i.e. energy output, frequency, source offsets and orientation);
b) method of source deployment;
c) trigger type (sensor, contact);
d) receiver type (geophone, accelerometer, offsets);
e) interpretation (software and methodology).

As most of the listed system parameters are not yet standardised within ISO 19901-8 (2023) and no standard reference test exists for marine SCPT, robust trials and testing for any newly developed marine SCPT system is required. The aims of such testing regime would be to determine the reliability and accuracy of the acquired data and to benchmark the newly developed system against established systems.

Within this context, this paper describes; the engineering considerations and optimisation of a novel system, intended for deployment from a new generation of robotic vessel; application and limitations of the set-up during trials and offshore operations; commentary on the in-situ data including challenges encountered during interpretation and comparison with laboratory collected small strain stiffness measurements is presented.

1.1. Concept of Operation

The novel system is named ‘Infinity Seismic Cone Penetration Testing System’ (Infinity SCPT). This new system is a seabed deployed CPT capable of seismic data acquisition.

For the purposes of the readers understanding of why certain engineering considerations were made in regard to the Infinity SCPT device configuration, it is pertinent to be aware of the ‘Concept of Operation’ (CONOP) for the system.

The device will be implemented onboard and deployed from Ocean Infinity’s Armada A78 series of autonomously operated surface vessel (ASV) in minimally to zero crewed mode. Therefore, there will be minimal personnel onboard to manually intervene with handling operations of separate seismic sources.

Infinity SCPT will be deployed and recovered, with minimal to zero intervention, through the A78 forward moonpool using a bespoke launch and recovery system (LARS) with latch been and cursor system. The vessel has no systems for the deployment of ancillary payloads such as separate seismic sources. The deployment set-up is presented in Fig 1.

Figure 1. Infinity SCPT deployment

Power, control and data transfer is provided to and from the device from the onboard interface system via a common fleet umbilical system. Data is further relayed to shore from the vessel and processed automatically.

2. Infinity SCPT Configuration

Driven by the overarching CONOP for the Infinity SCPT, the resulting configuration can be summarised as a deep push seabed CPT unit with an integrated seismic source and receivers, deployable as one through a single moonpool with a single lift, command and control umbilical. The un-crewed system was developed to be deployed fully remotely from onshore operations centres.

2.1. Deep Push CPT Technology

The newly developed system utilises a self-contained autonomous, hands-free, continuous push CPT system, incorporating “Single Twist™” (ST) technology developed by AP van den Berg (Storteboom and Woollard 2022).

The system comprises a foldable string of 350 mm long ST rods stored on a compact folder. The folder is capable of storing sufficient rods for a push to 80 m below seabed level, presented in Fig 2.

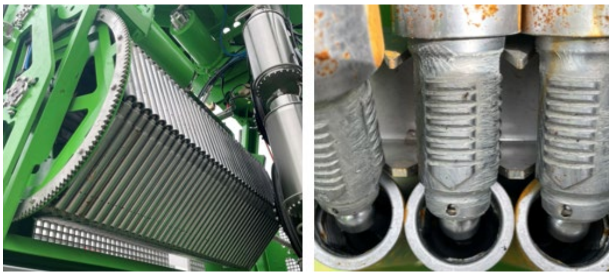

Figure 2. ST folder mechanism (left) and ST bayonet thread (right).

Transition of the foldable CPT string into a solid CPT string is facilitated via an electro-hydraulic “Twister” mechanism (Fig.3) whose purpose it is to connect and disconnect rods, through an application of up to 550 Nm torque, in an uninterrupted manner as the CPT cone and seismic module penetrates the seabed at 2 cm/s.

Figure 3. ST twister mechanism (left) and sprocket wheel for connection (right).

Correct positioning, constant speed and smooth connection of the ST rods is achieved via an electrically driven sprocket (Fig.3) with integral rod guiding blocks.

Seamless and efficient coupling and decoupling of the rod sections occurs through the ST bayonet thread allowing for complete coupling with only 27 degrees of rotation instead of 2180 degrees usually required with straight rods. An example of the ST thread is presented with Fig. 3.

2.2. Seismic source Technology

The seismic source includes two dedicated vertically propagating horizontally polarised shear wave (SH) sources, mounted in opposing directions and a compression wave (P) source. For purposes of deployment and recovery means through a dedicated moonpool onboard A78 series Armada vessels, the seismic source is attached to the main seabed CPT frame, as presented in Fig 4. The horizontal offset distance between the seismic source and the vertical axis of the SCPT array is 1410 mm as presented in Fig 5.

Figure 4. Infinity SCPT seismic source arrangement (yellow)

2.2.1. Seismic source design considerations

Key factors considered within the system design were 6-fold and intrinsically interlinked as presented below:

1. source centre to rod axis offset;
2. isolation of the seismic source from the main seabed CPT frame when deployed on the seafloor;
3. reaction force applied to source to ensure adequate coupling and energy transmission into the soil;
4. energy spectrum of the source;
5. sensor orientation to maintain alignment with the source and the Trigger;
6. seismic trace coherence and repeatability based on real-time QC evaluation.

Of these, 1 to 3 were the significant factors that dictated the source and mounting design whilst adhering to the CONOP. Factors 4 to 6 addressed the need for optimization, in terms of data quality and processing efficiency.

The seismic source was packaged in a way that the central point source can be accurately specified, necessary for interval velocity calculation. A lateral source offset towards the smallest of the range, recommended in ASTM D7400 (2019), was selected. This would reduce the effects of near surface refraction in heterogeneous soils therefore reducing potential travel time errors which are deemed to generally decrease with reduced source offset. (Kim et al. 2004).

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, which prevents transfer of shear waves through the frame and rods. The design also allows for some self-adjustment during deployment, to accommodate softer seafloor conditions, needed to maximize energy transfer into the soil.

Maintaining a close offset between the source and the rods (1.41 m as shown in Fig. 5) minimises the ray path correction effect, which is a more significant problem when analysing seismic results from systems that deploy an independent source, typically at offsets of as much as 5 to 6 m. The close offset also minimises the impact of interference at shallow penetration depths, resulting from other types of seismic waves.

It is critically important to ensure that the source is physically isolated from the CPT push rods, since seismic waves can travel through steel much more readily than through soil. Rod wave velocity is typically an order of magnitude greater than the shear wave velocity through soil, which means that a powerful rod wave can overprint or mask weaker SH waves arriving at the downhole receivers.

The reaction force exerted on the source should be sufficient to ensure it is in good contact with the soil, since SH waves travel mainly through the soil skeleton and are primarily controlled by confining pressure (effective stress) and soil density. Use of a variable ballasting system on the source allows for optimal coupling between the source and the soil but allows for reduction of the source embedment when testing at softer sites, to maintain source isolation.

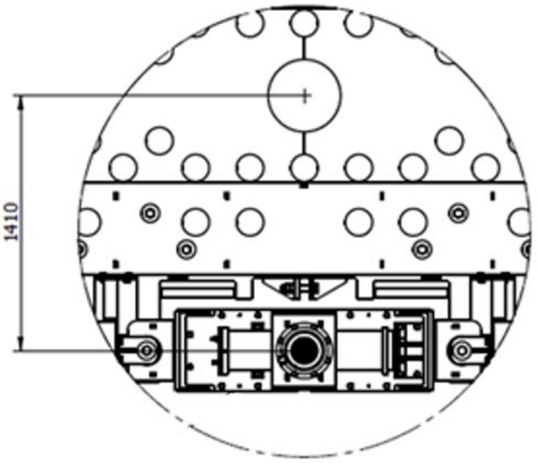

Figure 5. Schematic of seismic source depicting offset from seismic point source to SCPT rod axis.

2.3. Seismic acquisition system

For the context of this paper, the seismic acquisition system is considered to be made up of three key components: a) the seismic module, b) the trigger and c) the acquisition software (real-time QC analysis and recording of raw signals).

The seismic modules comprise a pair of triaxial arrays, consisting of tri-component accelerometer based sensors, with a vertical centre to centre offset of 500 mm. A reference trigger mechanism is a triaxial based sensor mounted on the seismic source adjacent to the point source directly in line with the point source and rod axis.

2.3.1. Seismic acquisition system, engineering considerations

When integrating triaxial arrays into a seismic module it is important to engineer the geometry so that the diameter of the module at the locations of each triaxial array are greater than that of the sections immediately below to optimise coupling between the arrays and the surrounding soil.

The seismic receivers used in the Infinity SCPT system are triaxial sensors, manufactured to match the acoustic response of the trigger. A dual-array receiver setup was employed, with the lower receiver mounted 0.5 m above the cone tip and with a further vertical separation of 500 mm between the two receivers. The selected array spacing, 500mm, facilitated compliance with the Infinity CPT geometry imposed by the CONOP, it also allows for acquisition intervals that facilitate both true and pseudo interval analysis. The horizontal receivers are oriented during equipment setup to ensure that their Y components are aligned with the SH hammer and Trigger Y axes.

To ensure that sufficient seismic signals are collected, the use of real-time QC software (SCPTQc) has been implemented in the Infinity SCPT system. This allows for immediate display of recorded seismic traces, assessment of trigger repeatability, receiver performance (repeatability in the time domain and response in the frequency domain), as well as trace coherence. Signal filtering and stacking is applied to assist in evaluating the data quality, with the objective being that the decision to collect additional shots at any given depth can be fully automated. Bad traces are flagged for further evaluation during data processing, to improve overall efficiency. This front-end QC software also provides metadata summaries for reporting. Data processing and report generation is undertaken with advanced customised software, configured for automated application (SCPTViewer).

2.3.2. Infinity SCPT Summary

The newly developed Infinity SCPT system was developed with a focus on speed of operations, repeatability, data quality and configuration for remote operations. The key features of this new system, pertinent to robust remote operations, were:

a) Removed requirement for CPT straight rod string support by utilising click-on modules, allowing rapid deployment without onboard crew;
b) Implementation of trigger sensors and recording signals on the same time base as the downhole receivers;
c) Isolation of the source from the frame to eliminate seismic waves rod strong wave travelling, while also minimising the offset and hence the ray path correction effect;
d) Increased source weight, to optimise seismic coupling and energy transmission into the soil column;
e) Orientation of the seismic cone to the SH source and the trigger Y components to optimise and simplify data processing;
f) monitoring the incoming seismic wave traces in real-time, by implementing real time QC software.

There were many other key engineering challenges in the development of the new system; however, the features listed above highlight the items considered most critical for achieving repeatable and robust results with minimal human input from operations through to data processing and report deliverables.

3. Testing

The implementation of this system followed a geotechnical product implementation cycle. The cycle presented in Fig.6, demonstrates on a generalised level the product development process.

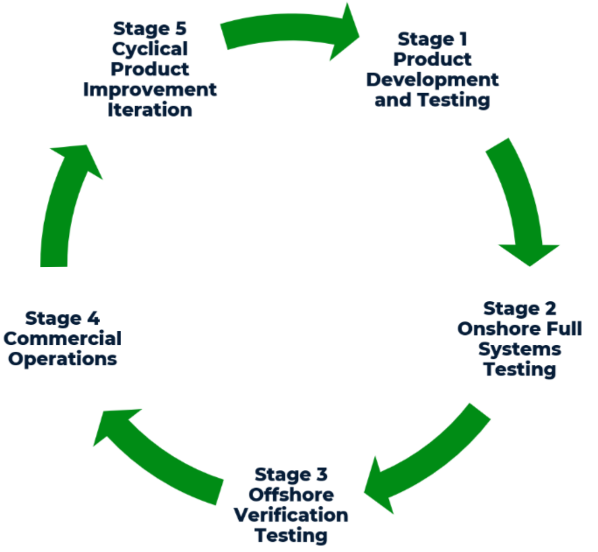

Figure 6. Geotechnical product implementation cycle

3.1. Onshore testing

Prior to the offshore verification and testing stage the system had several staged phases of onshore functionality, accuracy, and repeatability trials. These trials were aimed at proving the effectiveness of the individual constituents of the system, and in turn the whole system as intended within controlled conditions, providing opportunity to alter or improve any aspect as the phases were completed.

Systems checks included, but were not limited to, source repeatability, source amplitude and frequency distribution, trigger repeatability, trigger to receiver matching as well as seismic sensor matching.

Ensuring that all fundamental systems are optimised prior to progressing to wet tests and offshore trials is essential.

3.1. Offshore testing scope and rationale

As noted above there is no standard verification benchmark testing site for development of new marine SCPT equipment; however, this was considered critical for overall development of the systems. Therefore, offshore SCPT trials were undertaken at a site with extensive available data.

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.

Figure 7. Onshore testing setup.

3.1.1. Test Locations

To achieve the comparative aspects of the objectives set out, the proposed trials needed to be undertaken at a location where SCPT have been previously undertaken and the associated data available in the public domain.

Ten noorden van de Waddeneilanden Wind Farm Zone (TNWWFZ) located 56 km off the north coast of the Netherlands was selected as the site to undertake the offshore SCPT trials. Within the wind farm zone, specific exploratory locations were selected that fulfilled the following criteria; a) previously investigated, b) existing borehole with in-situ PS logging data, c) existing CPT data, d) existing SCPT data, e) outside of existing buffer zones and other areas of infrastructure, f) free of slopes and other seabed features and g) free of potential unexploded ordnance (pUXO) and certifiable as low as reasonably practicable (ALARP).

On the basis of these criteria, three target locations were identified, presented in Table 1.

Table 1. Identified target locations.

Test Location	Easting	Northing
TNW034	E667037	N5988099.
TNW025	E667214	N5988448
TNW076	E680986	N5991103.

3.1.1. Test Program

All locations (Table 1) showed similar conclusions; however, for the purposes of this paper detailed results are only presented for location TNW076.

3.2. Site conditions

The soil conditions were initially confirmed by a seabed CPT (TNW076-PCPT) and a borehole (TNW076-BH) to depths of 36 m and 78 m below seabed respectively. RVO (2020, 2022a). These records were corroborated through a seabed CPT undertaken as part of the offshore trials (TNW076-04A), presented in Fig. 8.

The geology within the depth of interest at the selected location has been interpreted to comprise of seven geotechnical soil units (RVO 2022b) ranging in geological age from Holocene to Late Holsteinian/Early Saalian.

Simply described, the soil at location TNW076 comprises a thin 0.5 m thick veneer of very loose silty fine and medium sand (GGM02) overlying a layer of dense to very dense fine and medium sand to 8.8 m (GGM23). From 8.8 m to 11.0 m exists a layer of medium dense to dense clayey sand (GB01A), overlying a layer described as, silty, clayey, high to extremely high strength dark grey slightly gravelly sand (GB01B), which in turn overlies loose to medium dense clayey sand to a depth of 46.0 m. (GGM41).

RVO (2022b) reports an abnormal seismic feature was identified in the geological ground model and it was impossible to track horizons within, this was denoted as the "Geobody". This volume mainly consists of two units and subunits A and B were therefore added as GB01A and GB01B. The grain size distributions from unit GB01B indicates that this is a well graded sand unit but CPT interpretations from the Geobody suggest an undrained response.

Fig 8. Presents the soil units and corresponding q_t, R_f, u and soil behaviour type (SBT) (Robertson 2010) encountered at TNW076-04A.

Normalised soil behaviour type (SBTn) (Robertson 2010 & 2016) plotted for each of the geotechnical units is presented in Fig. 9. The soils encountered at the location display a wide range of types and behaviours, from clay-like-contractive-sensitive (CCS) through to sand-like-dilative (SD) (Robertson 2016).

As a result, it is considered that the selected location provides an ideal verification location given the variation of complex soil types and hence mechanical stiffness-strength response.

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

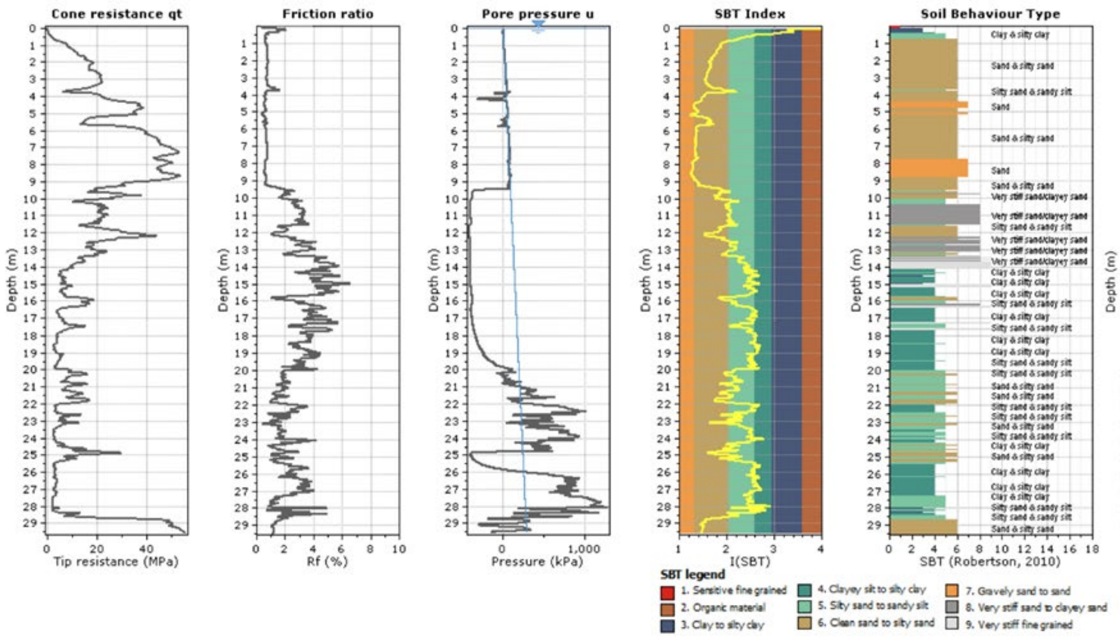

Figure 8. q_t, R_f, u & SBT TNW76-CPT-OI

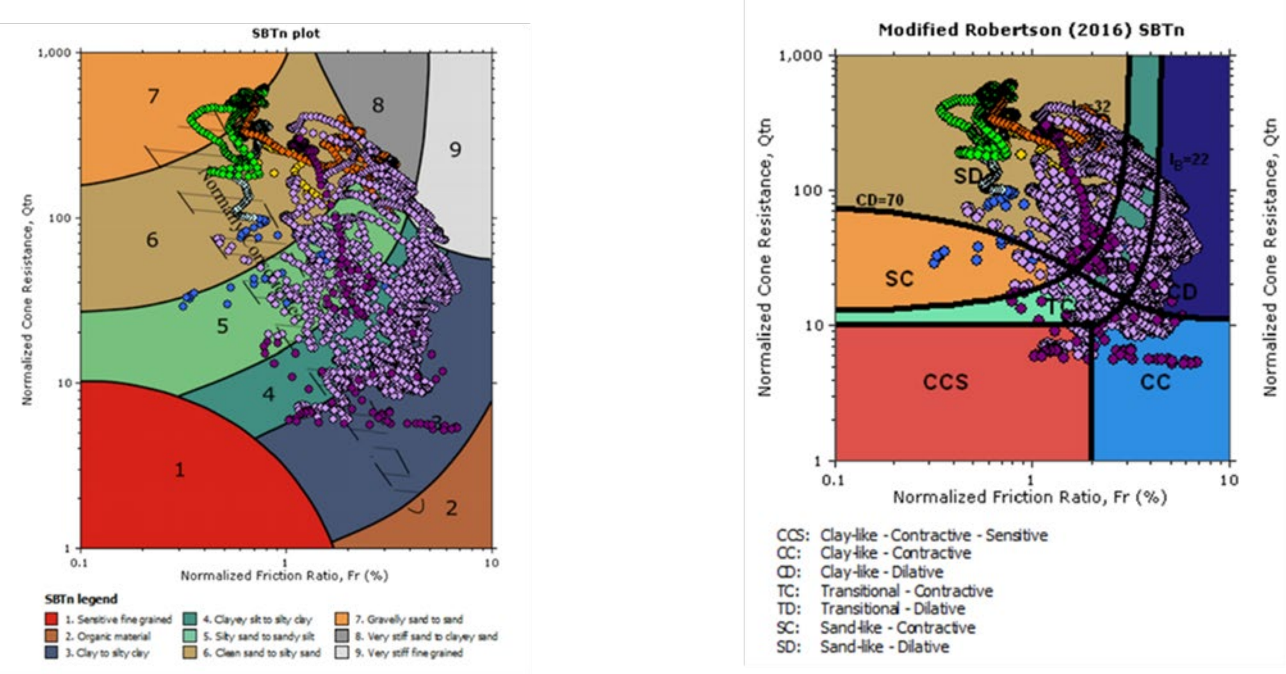

Figure 9. Normalised SBTn – TNW076-CPT-OI (Roberston 2010) left and (Robertson 2016) right.

measure of accuracy exists. Therefore, in order to demonstrate both the 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.

All calculated shear wave velocities were assessed both against existing data acquired at the same location (RVO 2020) and expected ranges for the soil strata encountered. 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.

Furthermore, and of more relevance for site-specific verification, a tree-based ML algorithm (XGBoost developers, 2022), was trained using all the v_s and CPT data measurements across the published data form the TNW and HKW offshore windfarms off the coast of the Netherlands. The number of data pairs used for the model training was 1,239 across both sites.

4.1.1. Comparison

A comparative assessment between the existing v_s data (RVO 2020) and the newly acquired data shows a very good comparison, with similar velocity profiles and

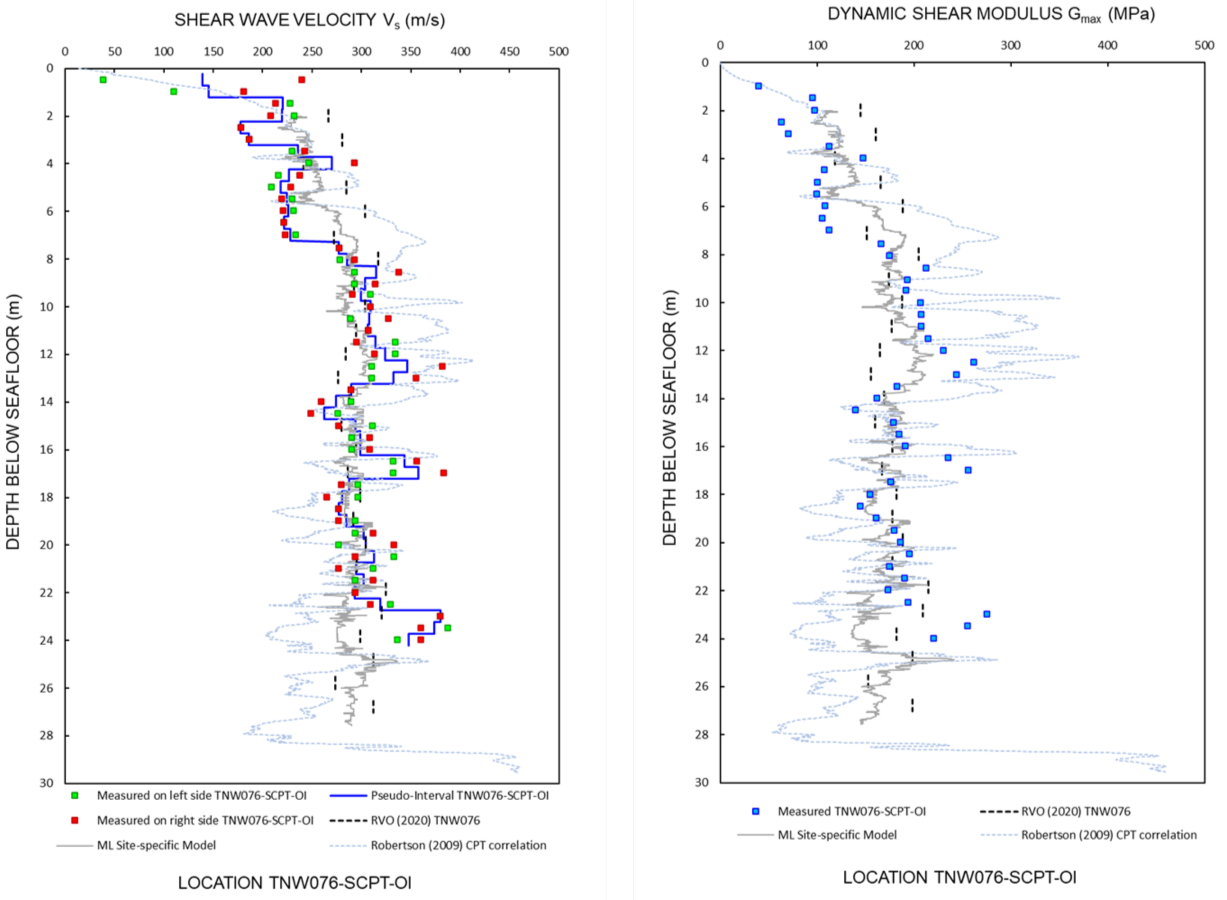

Figure 10. v_s (left) and G_{max} (right) measurements from TNW076-SCPT-OI

trends with depth. The calculated v_s and G_{max} for this selected location is presented in Fig. 10. Given the unknown differences between the system configurations, this provides demonstrable confidence in the comparative performance of the system versus well established SCPT systems previously deployed at the location.

A strong correlation exists between the derived v_s from the SCPT and the estimated v_s from Robertson (2009) was observed.

The strongest correlation exists with the ML algorithm This region-specific CPT-v_s ML algorithm showed to have better accuracy than both Mayne (2006) and Robertson (2009) by comparison of the r^2 values. Fig 10 shows a comparison of the shear wave velocities measured compared to the ML model. The very good agreement shown on Fig 10 further confirms the reliability of the newly developed systems presented in this paper.

Although it is widely recognised that the reliability of derived v_s in the upper 2 m to 5 m ISO 19901-8 (2023) may not be representative, there seems to be a coherent correlation between the SCPT derived v_s and the anticipated v_s as estimated from both Roberston (2009) and ML algorithm (2022).

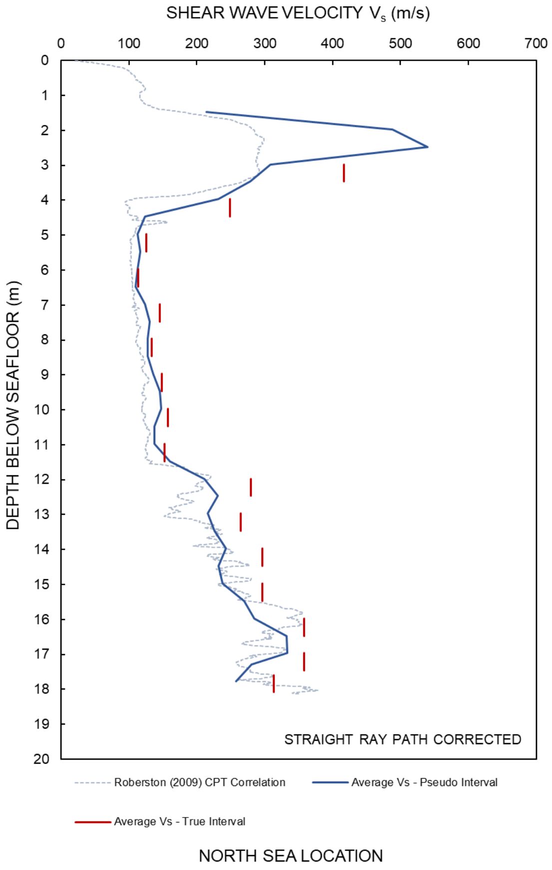

Figure 11. v_s measurements from selected location – North Sea

5. Commercial Operations

Following successful completion of offshore verification testing, the system was used on its first commercial operation at an unnamed site in the northern North Sea, accumulating approximately 700 m of SCPT pushes and acquiring v_s measurements from 4200 seismic shots. Within this project, both pseudo and true interval analyses were undertaken with results comparing well to other sources including Robertson (2009), as presented in Fig 11.

True interval derived v_s velocities match those of the pseudo interval analysis well, a small deviation is noted below 12 m depth below seafloor. This is probably due to increased SH velocity within denser layers, where we see shorter interval travel times. Hence, greater uncertainty exists as v_s increases.

Offshore verification testing and commercial operations presented product improvement opportunities which have already been implemented within the system's first cyclical product improvement iteration, the process demonstrated within Fig. 6.

6. Conclusions

This paper has presented a detailed overview of the development process for a new SCPT system for autonomous deployment. The Infinity SCPT has been proven to be a robust autonomous solution for acquiring reliable and accurate in-situ shear wave velocity (v_s) data. Through onshore testing, offshore trials at TNWWFZ and further commercial work, the system demonstrated its efficacy, producing v_s profiles which show very good agreement with existing data and established correlations. The incorporation of, and strong agreement with, a region-specific machine learning algorithm instils further confidence in the system capabilities and reliability.

It is also shown that engineering considerations, for compliance with CONOP for operations from Armada A78 ASVs have not comprised the system's primary function.

Demonstrating reliable and accurate in-situ v_s data and the associated issues, obstacles and uncertainties are well documented (e.g. Masters 2023). Considering that most of the listed system parameters are not yet standardised and with no standard reference test existing for marine SCPT, we see the development and trialling path documented within this paper as an exemplar for introducing novel marine seismic CPT systems to the industry and providing end users with confidence in said systems' acquired data.

6.1. Future work

It would be prudent for industry to work together to agree a standardised method for operational testing, system configurations, and to establish a benchmark verification testing protocol. Such a protocol should extend to include testing at an offshore verification site/location where such systems can be trialled, results compared and published. In essence, the benchmark verification protocol would aim to provide confidence to end users in the reliability and accuracy of the acquired data.

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