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Sustainable and accurate seismic tests to investigate small strain stiffness properties to complement the CPT

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ABSTRACT: An accurate quantification of shear wave velocity, V_s, is an important consideration in geotechnical design applications, particularly in the field of offshore wind turbine design, where increasing focus is placed on reliable small strain shear modulus (G_{max}) profiles. Seismic Cone Penetration Testing (SCPT) is a commonly utilised method to calculate V_s through measurement of shear wave travel times from a source to in situ receivers.

The Icone, a digital Cone Penetration Test (CPT), is easily extendable through addition of click-on modules to measure additional in-situ parameters. The Icone Seismic Module is an instrument utilised to investigate V_s and derive G_{max} of soils. This click-on module is automatically recognised, creating a true 'plug & play system'. It contains three accelerometers to receive left and right shear waves as well as compression waves. The Icone Seismic Module can be applied both onshore and offshore and has a 1,000m water depth rating.

Through incorporation of a seismic source within a ROSON seabed CPT system, seismic tests can be performed autonomously. The integrated seismic source described within this study contains a low energy impact source, and when coupled with high accuracy accelerometers within a seismic array an optimal configuration in terms of low noise is created.

Ocean Infinity, owner of several ROSON-ST systems with seismic modules, has already utilised the described system to acquire V_s measurements across various projects. Within this context, the paper describes the system advantages and operational advantages of the proposed system in practice.

Keywords: seabed CPT system; Seismic Cone Penetration Testing (SCPT); shear wave velocity (V_s); small strain shear modulus (G_{max})

1 INTRODUCTION

The small strain shear modulus (G_{max}) estimated from shear-wave velocity V_s is an essential input for prediction of ground motion due to earthquake excitation, for evaluation of foundations for vibrating equipment and behaviour of offshore structures during wave loading, and for deformations around excavations (Ghose 2012). More than four decades ago, seismic cone penetration testing (SCPT) was introduced as a rapid and economic means to obtain in situ V_s profiles in soil. The seismic cone penetration test (SCPT) provides multipoint simultaneous measurement of tip resistance (q_c), sleeve friction (f_s), pore pressure (u_2), and shear and compressional wave velocities (V_s and V_p respectively) following the down-hole geophysical testing strategy, but without using pre-drilling. (Lunne et al., 1997; Mayne & Campanella, 2005). Due to its cost effectiveness, speed of deployment and data quality the SCPT is one of the most commonly utilised in-situ methods for deriving the G_{max} of the soil (Donaghy et al., 2024). The acquired data of SCPT in combination with a newly developed seabed CPT system, intended for deployment from a robotic vessel, is reliable and accurate compared to the existing SCPT systems and will be described in this paper.

2 OFFSHORE SEISMIC CPTS

2.1 Developments in designing seismic CPT equipment

Since SCPT has been proven a useful addition to the standard CPT, the seismic CPT equipment has developed over the years. The use of a seismic cone offshore was reported nearly four decades ago (Campanella et al., 1986). During the years, several improvements have been made, mainly driven by industry and the availability of the digital technology. This resulted in fully integrated SCPT seabed systems with real time quality check (QC). In the next sections, some main developments are described.

Figure 1: Wireline CPT system (WISON-APB)

2.1.1 Wireline CPT system

More than three decades ago, the first designs were made to implement seismic in wireline offshore CPT equipment. The wireline CPT system (Figure 1, WISON-APB) is a pushing system specially developed for use on geotechnical vessels with a drill tower and moon pool.

A hydraulic cylinder configured with a cone, lowered and latched in the lower part of a drill string, performs a CPT in the soil directly below the bottom of the drill pipe. After each CPT of e.g. three-meter stroke, the tested soil is removed by drilling, so a new CPT can be performed. This procedure is repeated until the required CPT length is reached. Challenges of implementing seismic in the WISON-APB design were communication with and accurate positioning of geophones. During operations challenges like positioning of the seismic source, influences of the drill pipe and corresponding noise and difficulties with onboard quality checks needed to be solved. Difficulties to generate reproducible and reliable seismic data resulted in the requirement of a double array of geophones at a fixed distance to measure the true interval (Butcher et al., 2005).

2.1.2 Digital cone

With the availability of digital cones in 2005, the next step was the design of a seismic module, with an integrated data acquisition system, which can easily be stacked as a double array behind a cone (Figure 2, Icone with seismic module). This solution for communication and positioning simplifies integration in offshore CPT systems, enabling more offshore operators with the opportunity to add seismic to their CPT equipment.

Figure 2: Icone with seismic module

2.1.3 Seabed CPT system

The next logical step was the integration of the Seismic source in seabed CPT systems. A seabed CPT system (Figure 3, ROSON) is a pushing system that is deployed from a vessel with an A-frame from the rear deck or with a crane through the moon pool or over the side. Pushing systems can be hydraulically or electrically driven (like ROSON). In the latter case, the preassembled CPT string is clamped between two electrically driven wheels. By rotating these wheels, the string is pushed into the soil or retracted from the soil. Different cones, modules or samplers can be attached at the front end of the CPT string. The pushing system can be configured for pushing forces from 50 kN to 200 kN.

The umbilical winch includes all equipment to operate the seabed system. Depending on the water depth requirements, the winch can be supplied with a cable length from 200 m up to 4000 m.

Figure 3: Seabed CPT system (ROSON)

The next challenge was to develop a seabed CPT system for locations with increased water depths with a continuous push, which could operate autonomously. By incorporating the patented folding SingleTwist™ (ST) technology in the seabed CPT system (Storteboom et al, 2022), the safe and easy to handle ROSON-ST was created. The ROSON-ST is a deep push seabed CPT unit, in which the seismic source and receivers can be integrated. The unit is deployable as one through a single moonpool with a single lift command and control umbilical (Donaghy et al., 2024). The un-crewed system was developed to be deployed fully remotely from onshore. The ROSON-

Figure 4: Seabed CPT system (ROSON-3D-ST) with seismic source

ST (see Figure 4) is suitable for 80 m penetration, works with all Icone sizes and click-on modules and does not require any exterior CPT string support, assuring fast deployment, high productivity and increased safety. The maximum pushing capacity is often limited to 200 kN.

The integration of the seismic source in the Seabed CPT system (Figure 5) combines accurate CPT lengths in combination with an ideally positioned Seismic source to generate reproducible waves.

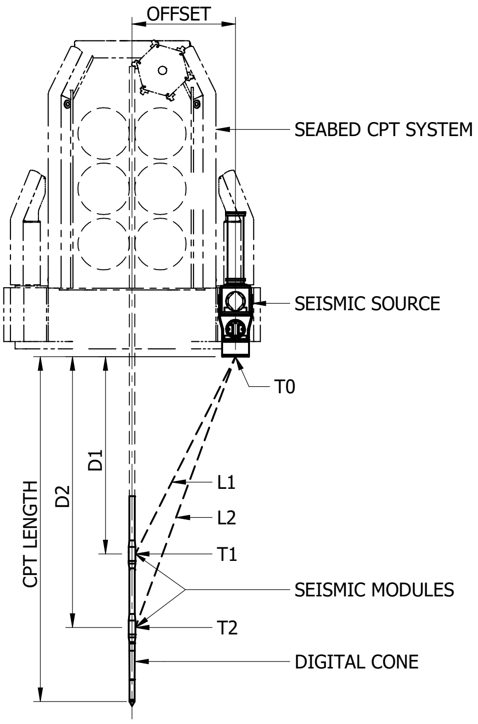


Figure 5: Schematic layout seismic set-up

The silence of the seabed system including seismic source is advantageous in reducing the noise level in combination with the highly sensitive accelerometer design. The high signal to noise ratio makes it easier to recognise the arrival of the generated wave. The available improvements of communication between seabed unit, vessel and office facilitates the implementation of a real time quality check system.

All these improvements over the years lead to a sustainable and accurate way of gathering reliable seismic data from the seabed CPT system.

2.2 Seismic source

The seabed CPT equipment consists of a seismic source with three hammers to generate seismic waves at the seabed. The seismic source is suspended in the ballast frame in a way to be stable during lifting and isolated from the ballast when placed on the seabed. When placed on the seabed the positioning accuracy is within +/- 30 mm at an offset of 1410 mm (Figure 5). The seismic source consists of three hammers. Two horizontal hammers for shear wave left and right and a vertical hammer for compression wave. The waves are generated by an electro-mechanical hammer that hits an anvil.

The hammer is designed to generate a reproducible wave to allow trigger repeatability and a wave in the correct frequency domain for the best propagation through the soil. A low frequency carries further and requires a lower sample rate. These design choices require an energy of 100 joules to generate a low impact, clean sine wave. In addition, it also has an environmental benefit by limiting the ocean noise pollution.

2.3 Seismic module

To investigate the elastic properties of the soil, seismic tests can be performed by the Icone Seismic Module (see Figure 2) with extremely sensitive sensors by a high signal to noise ratio. Elastic soil parameters are determined by measuring the propagation speed of an applied sound wave between two known depths. Mostly this is done by pushing the seismic module into the soil and stopping at 1-meter intervals. During the pause in penetration, a shear or compression wave is generated at surface level (T0) and the time required for the wave to reach the seismic sensors (T1/T2) is recorded. The arrival time difference between two consecutive seismic tests is used to calculate the shear-wave velocity and indirectly the elastic properties of the soil. Since the time difference between two consecutive measurements is approximately 2 ms (Storteboom et al, 2022), a very consistent measurement of the trigger signal is required. This requirement is met by using the same highly sensitive sensors for the trigger module and by placing this module in the immediate vicinity of the hammer.

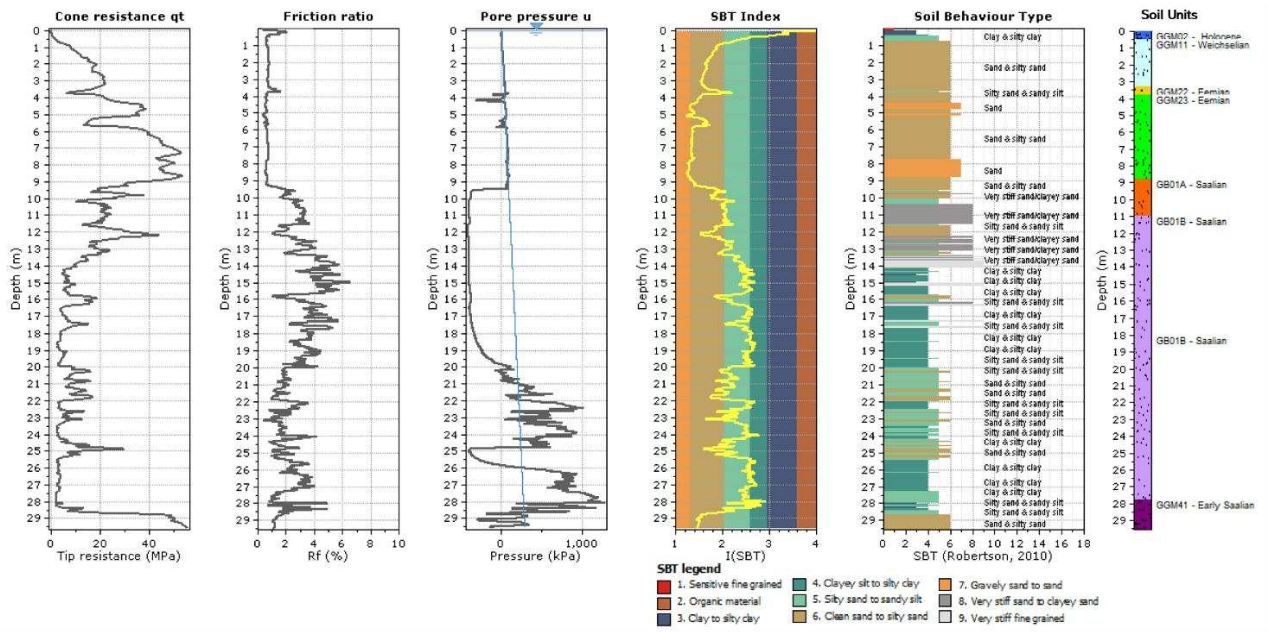


Figure 6: qt, Rf, u & SBT TNW76-CPT-OI

2.4 Data acquisition system

The Icone Seismic Module as well as the Icone are part of a modular data acquisition (DA) concept that is based on digital data transfer. The system consists of a digital data logger, called Icontrol, and the Ifield software for real-time data presentation. The output signals from the seismic sensors are being digitized inside the seismic module and from there transferred to the Icontrol data logger at surface level. The selected components of the DA system and software are designed to meet the required timing accuracy. Equal response of each module and synchronisation of the measured signals are key to determine accurate true interval shear-wave velocity. By measuring the trigger signal the pseudo interval accuracy can be improved by determining the timing difference between the trigger signals.

2.5 Operations

The system was initially developed and configured for implementation onto and deployment from Ocean Infinity's Armada A78 series of autonomously operated surface vessel (ASV) in minimally to zero crewed mode. The SCPT configuration and concept of operation (CONOP), which provides the readers with understanding as to why certain engineering considerations were made, is well described by Donaghy et al. (2024).

A key feature incorporated by Ocean Infinity, contributing towards the accuracy and efficiency of the SCPT, was the enablement of real time automated seismic wave trace assessment. To ensure sufficient seismic signal collection, the SCPT system incorporates real-time quality control (QC) software.

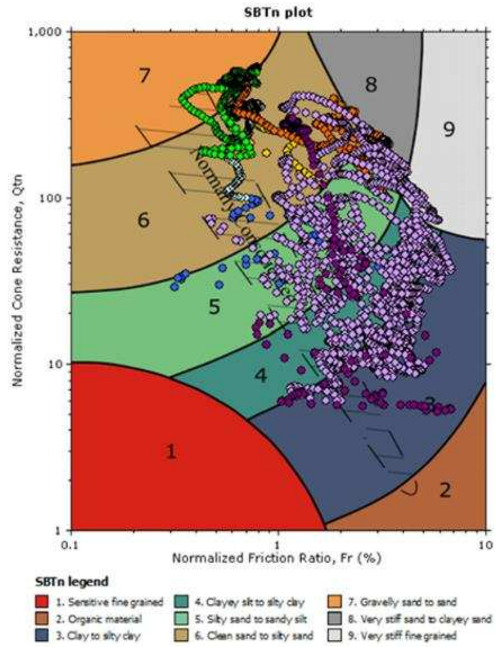
This software enables immediate display of recorded seismic traces and allows for comprehensive assessments, including trigger repeatability, receiver performance (time-domain repeatability and frequency-domain response), and trace coherence. Signal filtering and stacking can be applied to assist in evaluating the data quality, with the objective being that the decision to collect additional shots at any given depth can be fully automated. Poor traces can be flagged for further analysis during data processing, improving overall efficiency of acquisition. This front-end QC software also generates metadata summaries for reporting purposes.

3 SEISMIC CPT IN PRACTICE

The SCPT system described was first used offshore by Ocean Infinity, at Ten noorden van de Waddeneilanden Wind Farm Zone (TNWWFZ) located 56 km off the north coast of the Netherlands, on a set of offshore trials (Donaghy et al. 2024).

3.1 Site conditions

All locations at the trials site showed similar conclusions; however, for the purposes of this paper detailed results are only presented for location TNW076. Soil conditions at this location was initially verified by a seabed CPT and a borehole, reaching depths of 36 m



and 78 m below the seabed, respectively

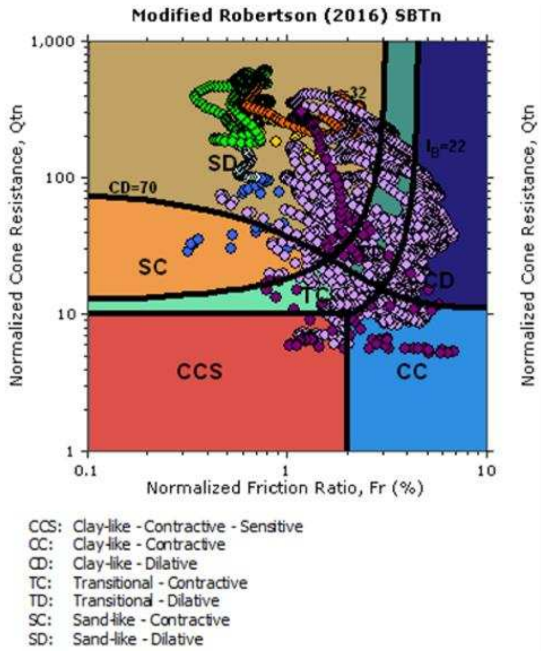


Figure 7: Normalised SBTn – TNW076-CPT-OI (Robertson 2010) left and (Robertson 2016) right

(Donaghy et al., 2024) and later corroborated by an additional seabed CPT conducted during offshore trials (TNW076-CPT-OI).

Figure 7 provides an overview of the soil units and associated parameters, including qt, Rf, u, and soil behaviour type (SBT) per Robertson (2010), encountered at TNW076-CPT-OI. Normalized soil behaviour types (SBTn) (Robertson, 2010 & 2016) for each geotechnical unit are presented in Figure 7, demonstrating a variety of soil types and behaviours, from clay-like contractive-sensitive (CCS) to sand-like dilative (SD) (Robertson, 2016). Consequently, the selected offshore trial location offers an ideal site for verification, given its complex soil profile and the associated range in mechanical stiffness and strength response.

4 RESULTS, ANALYSIS AND DISCUSSION

To demonstrate 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.

A comparative assessment between the existing V_s data (Donaghy et al., 2024) and the newly acquired data shows a very good comparison, with similar velocity profiles and trends with depth. The calculated V_s and G_{max} for this selected location are presented in Figure 8. Given the unknown differences between the system configurations, 2023 v 2020, this provides demonstrable confidence in the comparative performance of the system versus well established SCPT systems previously deployed at the location.

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

The strongest correlation exists with a machine learning (ML) algorithm which was trained using all the V_s and CPT data measurements across the published data from the TNW and HKW offshore windfarms off the coast of the Netherlands. 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. Figure 8 shows a comparison of the shear wave velocities measured compared to the ML model. This very good agreement shown on Figure 8 further confirms the reliability of this newly developed SCPT system.

5 CONCLUSIONS

Accurate reproducible data, focused on positioning and timing, lead to improved quality control "on site", which reduces the risk of having to repeat a test. This reduces the overall operational time. Ocean Infinity has improved this even further by performing a "real time" quality check after each shot. In addition, three shots are compared to each other to assess the signal quality. Reduced operational time and limited noise pollution contribute to the device's sustainable features.

Within trials at TNWWFZ and through further commercial work the system demonstrated its efficacy

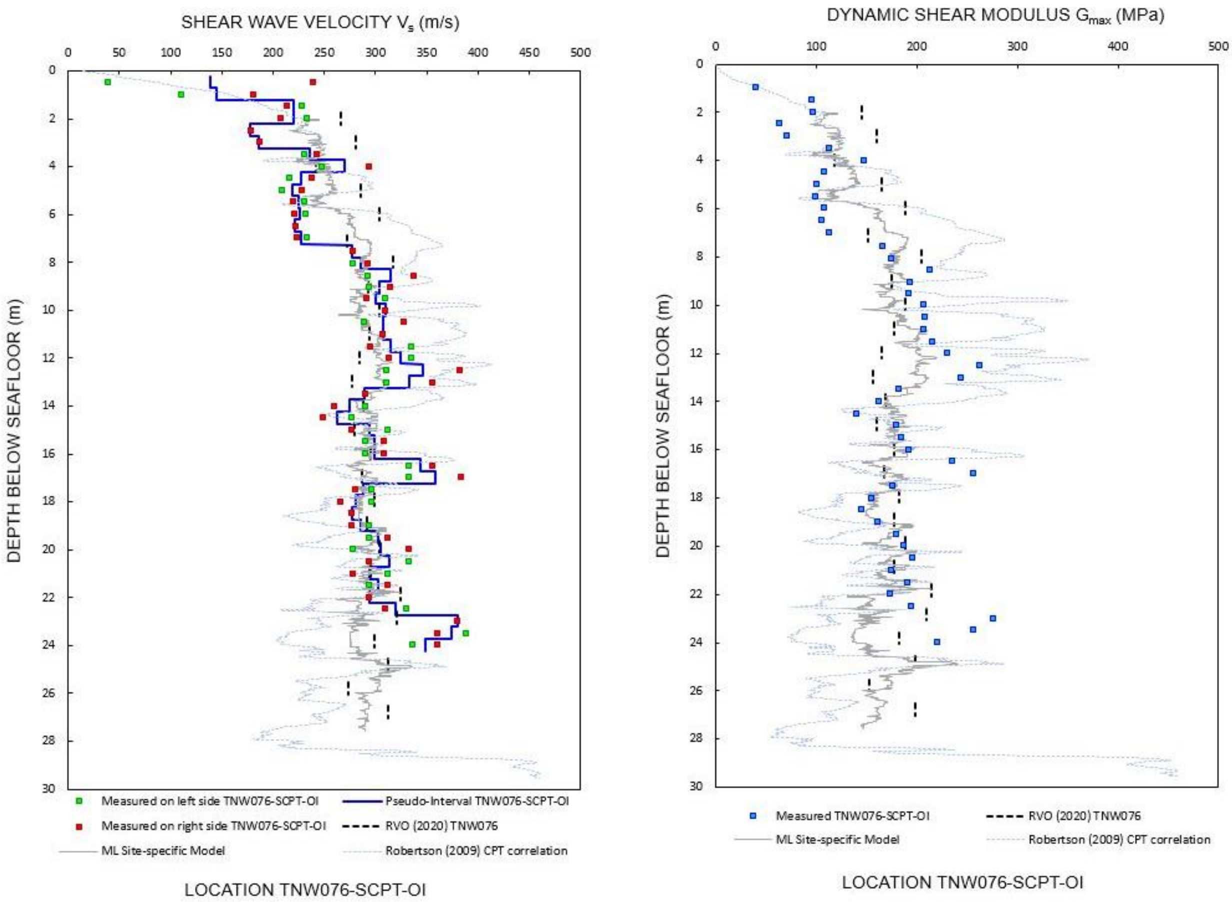


Figure 8: V_s (left) and G_{max} (right) measurements from TNW076-SCPT-OI

with V_s profiles showing good agreement with existing data and established correlations. The incorporation of, and strong agreement with, a region-specific machine learning algorithm reinforces confidence in the system capabilities. The SCPT has been proven to be a robust autonomous solution for acquiring reliable and accurate in-situ shear wave velocity (V_s) data.

AUTHOR CONTRIBUTION STATEMENT

A.T. Hoekstra: Abstract, introduction, offshore seismic CPTS, conclusions.
D. Donaghy: Abstract, operations, seismic CPTS in practise, results, analysis and discussion, conclusions.

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