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On the development of a novel marine seismic cone penetration testing (SCPT) system

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ABSTRACT: Following the conclusions of the Pile Soil Analysis (PISA) Project, increased emphasis is being placed on the acquisition of in-situ seismic (shear wave) velocity data, needed for evaluation of small strain modulus (G_{max}). This requires corroboration against laboratory-based measurements, to develop a reliable set of detailed foundation design parameters. There is a growing need to ensure that offshore testing of seafloor soils leads to accurate and reliable data with regard to measurement of shear wave velocity (V_s); a critical input parameter in the geotechnical design of wind turbines. Discussion among industry, clients, designers and contractors is needed on ways to improve seismic cone penetration test (SCPT) set-up, data acquisition and interpretation methodologies, to develop increased confidence in the V_s and G_{max} results. The discussion provided within this paper follows on from a previous paper, by presenting new observations and findings on; design, testing and means of utilisation of a dual-array non-drilling mode seismic cone penetration test (SCPT) device and seafloor seismic source. Within this context, the paper describes; engineering considerations and optimisation of this novel technology, for deployment from a new generation of robotic vessel; recommended offshore equipment set-up and operation; commentary on seismic data quality, including challenges encountered during seismic data acquisition, processing and interpretation. The paper also presents a result-based evaluation of SCPT and CPT data collected at a reference location in the southern North Sea. Finally, a methodology is reviewed and extended, for detection of soil cementation and microstructure, using a combination of normalised shear wave moduli and cone penetration test results.

Keywords: Soil cementation; seismic cone penetration test (SCPT); shear wave velocity (V_s); shear modulus (G_{max}).

1 INTRODUCTION

Design of offshore wind turbine foundations requires evaluation of small strain stiffness (G_{max}), to study foundation pile response to dynamic loading. Accurate measurement of dynamic moduli is critical when modelling structural performance, as with steel monopiles. The seismic cone penetration test (SCPT) is a commonly used and cost-effective technique for obtaining reliable in-situ values of G_{max}.

Dynamic soil response at low shear strain levels is best obtained indirectly from shear wave velocity (V_s) with bulk soil density (ρ) measurements, wherein

$$G_{max} = \rho \cdot V_s^2 \tag{1}$$

SCPT hardware and methodology varies somewhat between the onshore and offshore, however data interpretation methods are generally similar. Onshore SCPT configuration, design and methodology was documented by Campanella & Davies (1994), which led to an ASTM test specification D7400/D7400M-19 (2019) and specification ISO 19901-8 (2023). Still, significant challenges remain offshore on how to meet minimum data quality standards.

Key considerations to obtaining high quality SCPT results offshore include; a) seafloor seismic source characteristics (peak energy output, frequency bandwidth, source offsets from the SCPT push rod string, hammer orientation, method of deployment, seismic trigger type and orientation about the vertical axis); b) downhole receivers (geophone or accelerometer-type, vertical spacing within the downhole tool, orientation about the vertical axis); and c) data acquisition, quality control, data post-processing and interpretation (by means of software-based seismic analysis).

This paper describes; critical considerations for optimization of an SCPT system designed for deployment from a robotic vessel; set-up for efficient offshore operation; and data quality requirements during data acquisition for efficient and reliable data processing and interpretation. The paper also presents a robust methodology for identifying soil cementation and microstructure, and presents an example from a reference North Sea location.

2 INFINITY SCPT

The SCPT system is referred to in the paper as the ‘Infinity Seismic Cone Penetration Testing System’ (Infinity SCPT) and is presented in Figure 1. A detailed description of the seafloor equipment and method for deployment and recovery was given by Donaghy et al (2024).

Figure 1. Infinity SCPT seafloor pushing apparatus (frame) and its side-mounted seismic hammer source.

2.1 Seafloor Seismic Source

The seismic source is deployed to the seafloor along with the Infinity SCPT. It comprises two electro-mechanical hammers, mounted on vibration isolation dampers in opposing directions (Left and Right, or L and R), to generate horizontally polarised vertically-propagating shear (*SH*) waves. A third hammer is mounted vertically, to generate omnidirectional compression (*P*) waves. A variable ballast system ensures that seismic energy is transferred into the soil. The horizontal offset (at the seafloor) between the seismic source and the vertical axis of the rod-string is fixed at 1.41 m. This small source offset minimizes interference from other types of seismic (Surface) waves, which typically are created by the source and travel laterally, at shallow depths.

A trigger sensor (triaxial sensor) is mounted on the seismic source near the hammers, providing a signal that registers the instant that each hammer impacts its respective anvil after being fired. The topside data acquisition system simultaneously records the trigger and downhole seismic receiver signals, needed for accurate interpretation of *SH* and *P* wave velocity. Historically, offshore SCPT systems typically did not record the trigger signal (Marsters et al, 2023). It can be shown that minor timing variations result in significant uncertainty when calculating interval velocities.

The SCPT tool is mounted on the bottom end of a CPT push rod-string, which on the Infinity SCPT is coiled on a storage drum, mounted inside the pushing apparatus (Figure 1).

2.2 Downhole Seismic Receivers

The Infinity SCPT tool houses sensors for measuring tip resistance, sleeve friction, dynamic porewater pressure and cone inclination. Dual-array triaxial seismic receivers are mounted 530 mm and 1030 mm above the cone tip, giving a fixed vertical separation of 500 mm. The receivers are mounted orthogonally in the X, Y and Z direction, with the Y axis set to be co-aligned with the L and R (horizontal) seismic hammers. The arrangement of the SCPT tool and seismic source is shown in Figure 2, along with (direct ray) travel paths from the seismic source to the receivers.

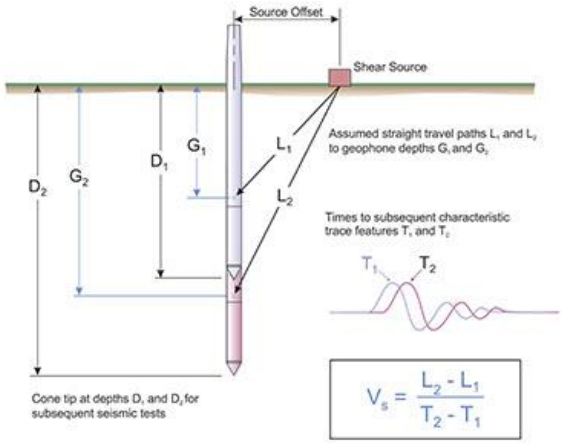

Figure 2. Diagram showing seismic source at mudline and the downhole receivers mounted just above the SCPT tool.

The SCPT test allows evaluation of *SH* velocity, by comparing the phase, or time difference between shear waves for all receivers (pseudo-interval); or just between upper and lower receivers (true-interval). Seismic tests are done during pauses in cone penetration, typically on a 0.5 or 1.0 m interval.

2.3 Data Acquisition

Seismic Trigger and Receiver signals are converted to digital signals and transmitted to the data acquisition system, which records a 600 ms record during each seismic test.

The Infinity SCPT data acquisition system uses a data sampling frequency of 5 kHz, giving a time step resolution of +/-0.2 ms. A bandwidth-limited signal must be sampled at a frequency higher than the Nyquist rate, or twice that of the highest frequency in the raw signal. SH waves possess a bandwidth of about 300 Hz, so a 5 kHz data sampling rate is acceptable for detection of shear (SH) waves.

Data sampling at slower rates can induce signal aliasing and phase shift errors. Sampling at a rate above the Nyquist frequency is unnecessary. To avoid data quality and processing complications, receivers should be co-aligned with each other and with the source. They must also be matched in terms of their sensitivity, frequency response and damping.

2.4 Data Quality

The presumption that seismic waves follow a vertical travel path is incorrect, as illustrated in Figure 2. A velocity correction for travel path geometry must be done, to address the source offset. Minimizing the offset reduces the magnitude of the velocity correction, which is greatest near the mudline but reduces with depth (Butcher & Powell, 1996). The small source offset present in the Infinity SCPT also reduces interference from other types of seismic waves, which exist near the mudline. Co-alignment between the source and downhole receivers ensures the Y response is dominant, simplifying processing. The SCPT tool must not rotate during penetration.

SCPT signal coherence is improved by taking multiple shots at each test depth. Signals are stacked to cancel out random noise, thus increasing signal-to-noise ratio (*SNR*). Seismic signals can be analysed by cross-correlating the most recently acquired signal with the stack of the other signals, for each hammer and at each test depth. This allows rejection of bad traces and the SCPT operator is then able to identify when an adequate number of tests have been acquired. Signals may be also be digitally filtered, to reduce high frequency noise and interference from transients generated within the equipment (vibrations induced by sea currents and sea surface waves).

Figure 3 presents a gain-corrected shot gather of receiver signals for the Left hammer and Y-component. A Moving Event Window (*MEW*) is shown in yellow, to identify the SH wave arrivals. Signal processing is undertaken only on the signals within the *MEW*. Similar shot gathers are typically produced for the R and V hammer directions (for the Y and Z components, respectively).

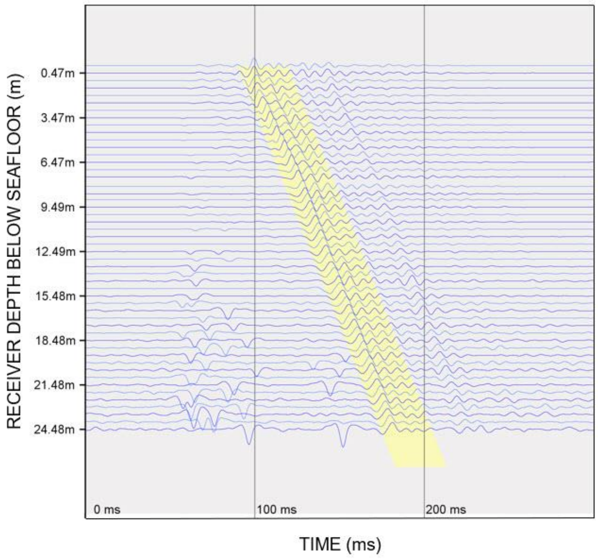

Figure 3. Processed downhole receiver signals for Left Hammer and Y component. Upper and Lower receiver traces shown.

2.5 Data Processing

Seismic signals may be processed in real-time, or after data collection has been completed. Processing involves: (a) data cleaning (rejection of suspect or bad traces); (b) Zero-time correction; (c) definition of the *MEW*; (d) signal filtering and signal stacking; (e) evaluation of signal phase (interval travel time); (f) calculation of interval velocity; (g) ray path correction; (h) forward modelling (if required); and (i) final reporting.

2.6 Analytical Uncertainty

A degree of uncertainty exists when calculating V_s or V_p according to limitations in data acquisition sensitivity. For a sampling frequency of 5 kHz, interval travel times display an error from +/-0.2 ms (for one receiver) to +/-0.4 ms (two receivers), as shown in Figures 4 and 5 for a fixed 0.5 m interval.

Cross correlation is a more reliable method than manually picking first wave arrivals, as it removes subjectivity. Seismic signals are analysed in the L and R hammer directions to yield an average interval velocity. A correction is applied for the source offset.

Source repeatability and signal coherence are key considerations. Maximum coherence is achieved through careful test execution and signal processing, comprising: (a) removal of lower quality signals; (b) correcting for frequency-based attenuation; and (c) evaluating phase-shifting related to sensor orientation and dynamic performance during testing.

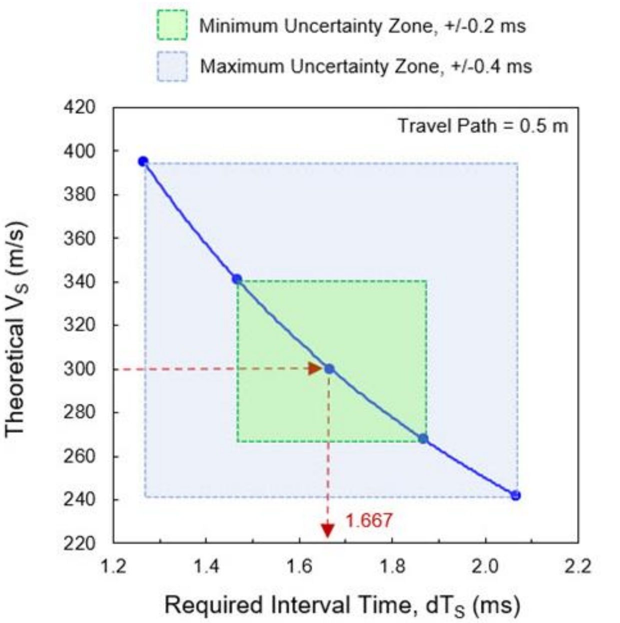

Figure 4. Potential Vs error with interval time (dTs). An assumed SH wave velocity of 300 m/s gives an interval time of 1.667 ms. An error of +/-0.4 ms reflects a dual-receiver setup (5 kHz data acquisition system).

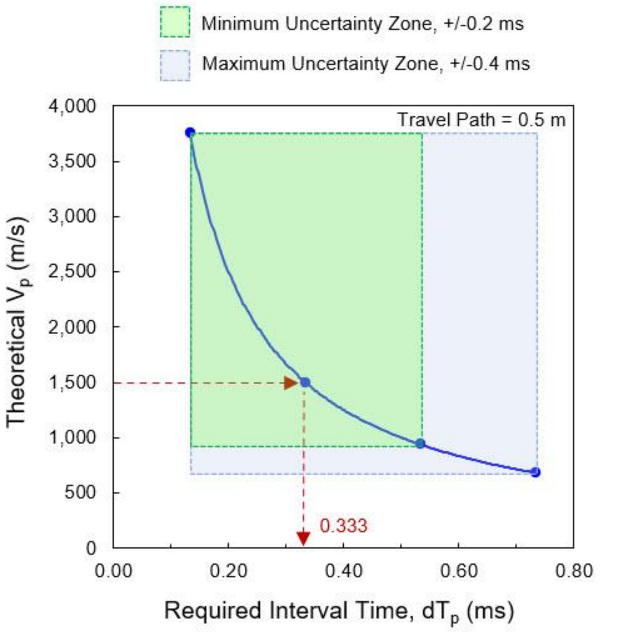

Figure 5. Potential Vp error with interval time (dTp). An assumed P wave velocity of 1,500 m/s gives an interval time of 0.333 ms. An error of +/-0.4 ms reflects a dual-receiver setup (5 kHz system).

3 FIELD TESTING AND ANALYSIS

The Ten Noorden van de Waddeneilanden Wind Farm Zone is located 56 km off the north coast of the Netherlands. Results from a field trial at TNW076-SCPT-OI are presented below.

3.1 Geotechnical Site Conditions

Donaghy et al (2024) summarized soil conditions at the TNW076-SCPT-OI location. From the mudline, the soil profile comprised: very loose silty fine-to-medium sand (to 0.5 m), over dense to very dense fine-to-medium sand (to 8.8 m), over medium dense to dense clayey sand to high strength silt, clay and slightly gravelly sand (to 28.5 m), over loose to medium dense clayey sand (to +46 m).

Figure 6 presents test results overlaid on a CPT classification chart (Robertson, 2016). The CPT response ranged from clay-like-contractive-sensitive (CCS) to sand-like-dilative (SD).

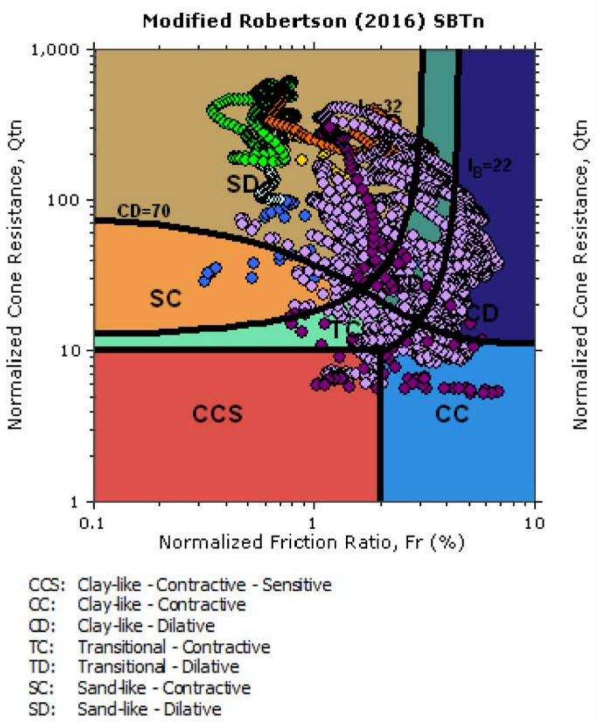

Figure 6. Normalised CPT classification chart (Robertson 2016) for location TNW076-SCPT-OI.

3.2 SCPT Data Interpretation

For comparison, an empirical correlation (Roberston 2009) was used to predict V_s from CPT data. A strong correlation was observed between measured V_s and the estimate from Robertson (2009). A stronger correlation existed between measured V_s values and site-specific *ML* predictions (Donaghy et al, 2024).

Empirical correlations do not fully predict CPT response for all soils, as they are based on a range of soil types with differing stress histories. However, these correlations excluded soils with cementation and internal bonding (microstructure).

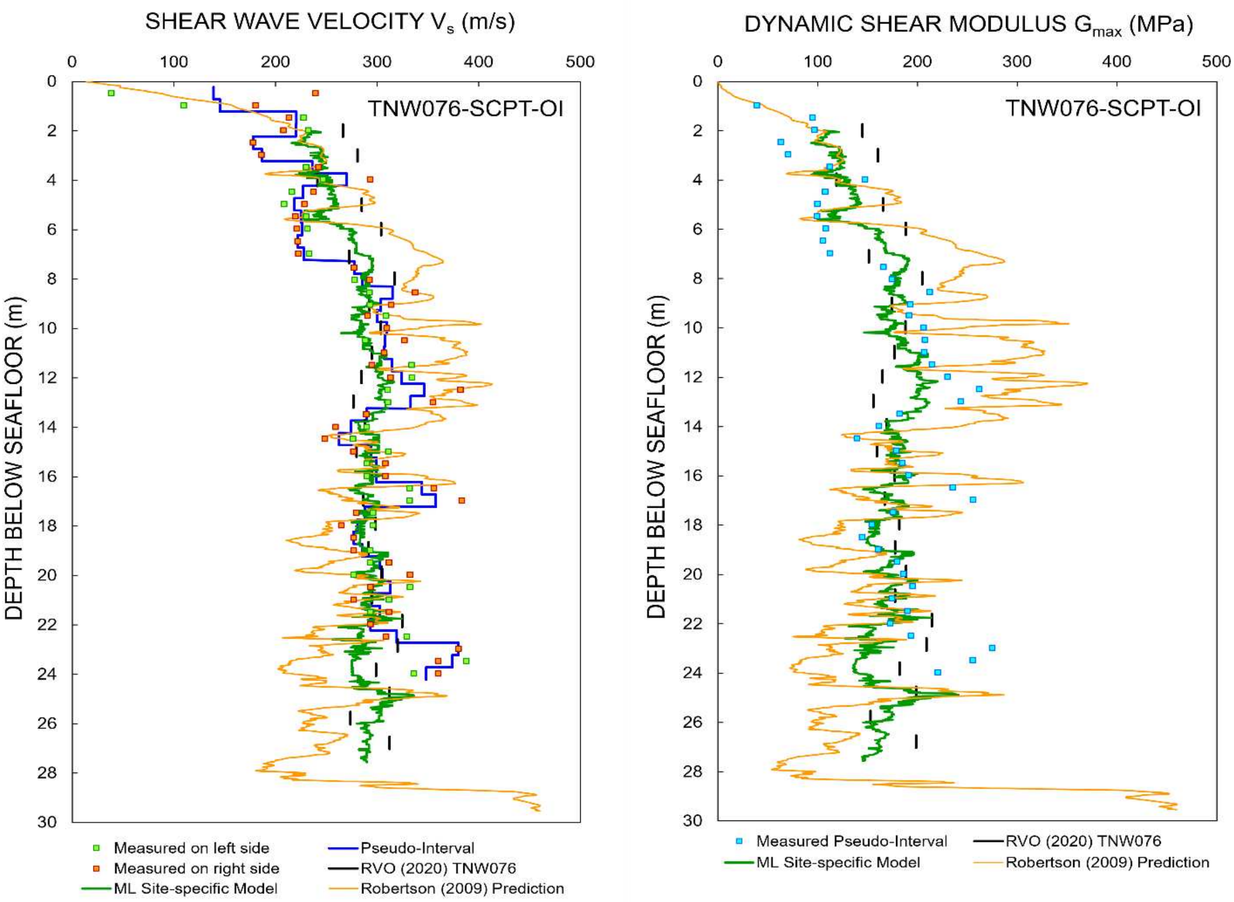

Figure 7. Profiles of measured and predicted Vs and Gmax from location TNW076-SCPT-OI.

Measured shear wave velocities averaged about 300 m/s below 8 m (Figure 7) and have an uncertainty of +/-35 m/s (Figure 4). It is possible to reduce this error by oversampling the signal and interpolating between datapoints.

Bulk density of soil was evaluated from a CPT-based correlation (Robertson and Cabal, 2022) to allow calculation of G_{max} from Eq. (1).

3.3 Soil Cementation and Microstructure

CPT data from young, unaged soils of Holocene age tend to plot lower in the *SBTn* chart than those of Pleistocene age (Figure 6). As noted, this chart may not identify cementation effects. Other methods are required for identifying 'unusual' soil conditions.

SCPT classification charts based on normalized V_s for Holocene and Pleistocene age soils, developed by Eslaamizaad and Robertson (1997) were modified by Schneider and Moss (2011). Therein, normalized cone penetration resistance Q_{tn} is:

$$Q_{tn} = [(q_t - \sigma_{vo}) / P_{atm}][P_{atm} / \sigma'_{vo}]^{n} \qquad (2)$$

where total and effective vertical stresses are denoted as σ_{vo} and σ'_{vo} respectively. Atmospheric pressure P_{atm} is equal to 100 kPa and the stress exponent n varies with SBTn, as:

$$n = 0.381\, I_c + 0.05\, (\sigma'_{vo} / P_{atm}) - 0.15 \qquad (3)$$

I_c is the CPT-based Brittleness Index (Robertson, 2009). Schneider and Moss (2011) calculated small strain rigidity index (I_G) as:

$$I_G = G_{max} / q_{net} \qquad (4)$$

where q_{net} is obtained from:

$$q_{net} = q_t - \sigma_{vo} \qquad (5)$$

The equation for calculating modified small strain rigidity index (K_G*) becomes:

$$K_G^* = (G_{max} / q_n)\, (Q_{tn})^{0.75} \qquad (6)$$

Figure 8 presents an SCPT classification chart incorporating small strain response, that provides a clear indication when soil cementation and microstructure may be present. Combined SCPT and CPT based-results obtained from TNW076-SCPT-OI are shown. Results plotting above the Normalized Rigidity Index line ($K_G* = 330$) indicate that some of soils at TNW076-SCPT-OI are likely to be strongly cemented and may possess microstructure.

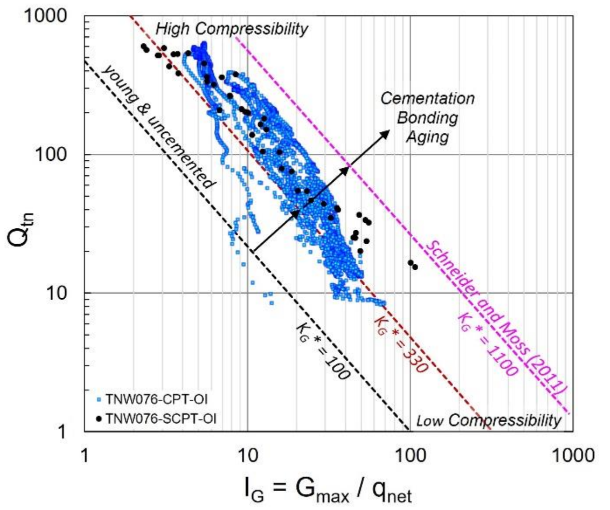

Figure 7. Normalized CPT and SCPT classification chart modified after Schneider and Moss (2011), showing results from the TNW-SCPT-OI North Sea location.

4 CONCLUSIONS

Offshore wind turbines sustain lengthy periods of cyclic loading. Dynamic moduli are critical input parameters needed for detailed foundation design. A North Sea case study was presented, to show how CPT and SCPT results can be combined to identify the presence of soil cementation. Further study, including advanced laboratory testing, is being carried out to verify these findings. Additional study and discussion is needed on ways to reduce measurement error and to develop more reliable and useful site characterization methods, considering the possibility of unusual soil conditions being present.

AUTHOR CONTRIBUTION STATEMENT

H.A. Christian: Data curation, Formal Analysis, Writing - Original draft. **D. Donaghy**: Funding acquisition, Conceptualization, Supervision. **S. Whyte**: Reviewing and Editing.

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