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The SOURCE project: Quantifying and reducing the uncertainties associated with in situ stiffness measurements

Le projet SOURCE: Quantifier et réduire les incertitudes associées aux mesures de rigidité in situ

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ABSTRACT: Offshore wind turbine foundations account for a significant portion of a wind farm's capital cost, and design optimisation is becoming increasingly important. While the soil or rock in situ shear stiffness is a vital input parameter in several foundation design methods, the reliability of current in situ stiffness measurements and interpretation techniques is known to be variable. The SOURCE (Improved In situ Stiffness Measurement for Offshore Wind Foundation Design Considering Uncertainty Repeatability and Common Sources of Error) project is underway to quantify and reduce uncertainty in soil/rock in situ stiffness measurements and improve the predictive capability of offshore foundation design methods. The project involves multi-method geophysical and in situ field testing at three onshore sites, each having distinct ground conditions representative of offshore sites. The in situ testing is supported by advanced laboratory testing on high-quality samples. This paper reviews typical challenges and presents preliminary insights from the carefully controlled experiments, which aim to identify inter and intra-method variability in estimating the small strain in situ stiffness.

RÉSUMÉ: Les fondations des éoliennes offshore représentent une part importante du coût d'investissement d'un parc éolien, et l'optimisation de la conception devient de plus en plus importante. Bien que la rigidité au cisaillement in situ du sol ou de la roche soit un paramètre d'entrée essentiel dans plusieurs méthodes de conception de fondations, la fiabilité des techniques actuelles de mesure et d'interprétation de la rigidité in situ s'avère très variable. Le projet SOURCE (Amélioration de la mesure de rigidité in situ pour la conception des fondations d'éoliennes offshore en tenant compte de l'incertitude, de la reproductibilité et des sources d'erreur communes) est en cours pour quantifier et réduire l'incertitude dans les mesures de rigidité in situ du sol/roche et améliorer la capacité prédictive des méthodes de conception de fondations OWT. Le projet implique des essais géophysiques et in situ multi-méthodes sur trois sites terrestres, chacun présentant des conditions de sol distinctes représentatives des sites offshore. Les tests in situ sont soutenus par des tests avancés en laboratoire sur des échantillons de haute qualité. Cet article passe en revue les défis typiques et présente des informations préliminaires issues d'expériences soigneusement contrôlées, qui visent à identifier la variabilité inter et intra-méthode dans l'estimation de la rigidité in situ des petites déformations.

Keywords: In situ stiffness; seismic tests; shear wave velocity.

1 INTRODUCTION

Recent research has led to the development of new offshore wind turbine (OWT) foundation design procedures and frameworks informed by numerical modelling and field testing (Byrne et al., 2017, Jardine et al., 2023). While these advancements have led to important innovations, there remains significant uncertainty in the definition of input parameters including the small strain in situ stiffness (G_{max}). The latter is an important input into soil constitutive models for finite element analysis and simplified 1D analysis frameworks (see e.g. Byrne et al., 2020, Zdravković et al., 2020). The stiffness of the soil also influences the eigen-frequency of the turbine-tower-foundation system, which must lie outside key excitation frequencies to avoid resonance (Arany et al., 2016). As OWT foundations substantially impact the cost of wind farms, accurate measurement of G_{max} at an early stage is crucial for optimisation. The in situ stiffness is typically characterised by measurement of shear wave velocity, V_s, in seismic tests. Errors in the measurement of V_s are amplified in the subsequent calculation of G_{max}, due to the squaring of V_s in its formula ($G_{max} = \rho V_s^2$; where ρ is bulk density of soil).

Existing field and laboratory methods can exhibit significant test method dependency, data scatter, and poor correlation with laboratory measurements. The challenges in data acquisition and interpretation include e.g. source arrangements, geophone arrays and interval distance, selection of arrival time and ray path assumptions (Parasie et al., 2022). Sampling disturbance, material anisotropy, fractures and inclusions also play a role and can lead to stark differences between laboratory and in situ stiffness (Taborda et al., 2019). Masters et al. (2019) reviewed the most common methods conducted offshore including field P-S suspension logging (PSL), seismic cone penetration testing (SCPT) and laboratory resonant column (RC) and bender element (BE) testing. Significant scatter was seen in the results. Figure 1 plots another example from a sand profile in the Ten noorden van de Waddeneilanden (TNW) wind farm zone (RVO, 2023) that highlights the difficulties in establishing consistent profiles and integrating data sets. Difficulties in accurate measurement of V_s are not unique to offshore projects. Liu et al. (2017) found variations in in situ stiffness from SCPTs of up to 50% from adjacent areas at a dense marine sand site, while large variations of up to 2GPa were observed in SCPT tests at a relatively homogenous chalk site (Vinck et al., 2022).

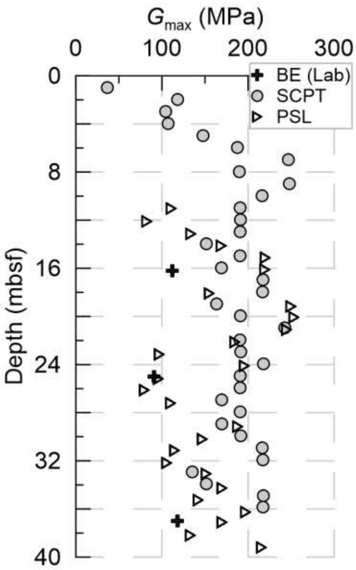

Figure 1. Example of divergence between methods to determine G_{max}: example from TNW-016-BH-CPT.

1.1 The SOURCE Project

The SOURCE (Improved insitu **S**tiffness measurements for **O**ffshore foundation design considering **U**ncertainty, **R**epeatability and **C**ommon sources of **E**rror) is a collaborative research project that aims to reduce the uncertainty associated with soil and rock in situ stiffness measurements and minimise the impact on the predictive capability of offshore foundation design methods. Comprehensive multi-method geophysical, in situ and laboratory testing is planned at three onshore test sites, in order to create benchmark datasets and develop robust, standardised guidelines for high-quality stiffness measurements. Each site involves drilling and sampling along with invasive methods including SCPTs, PSL, Down-hole (DH) and cross-hole (CH) borehole geophysics and pressuremeter tests (PMT). The field testing is supported by the extensive laboratory research undertaken at the University of Glasgow. The criteria for site selection are set to (i) be representative of typical profiles commonly encountered offshore and (ii) include sites where soil characterisation poses significant challenges. Site 1 was located at a disused chalk quarry in Kent close to the previous field-testing summarised by Jardine et al. (2023). Site 2 employed a dense sand site in Northern Germany while Site 3 will target over-consolidated clay ground conditions onshore UK.

2 IN SITU SHEAR STIFFNESS MEASUREMENTS

The in situ testing programme integrates various invasive and non-invasive methods each with unique capabilities and limitations; invasive seismic methods considered are shown in Figure 2. The SCPT and DH both work on the same principle, where a surface seismic source (a manually operated sledgehammer dropped onto a plate) generates seismic waves. These waves travel through the soil strata and are recorded by uni or multi-component sensors placed at depth. For the measurement of true interval velocity, a relative time difference between the received signals from dual receivers is calculated. Multiple shots are recorded at a particular depth to improve the signal-to-noise ratio.

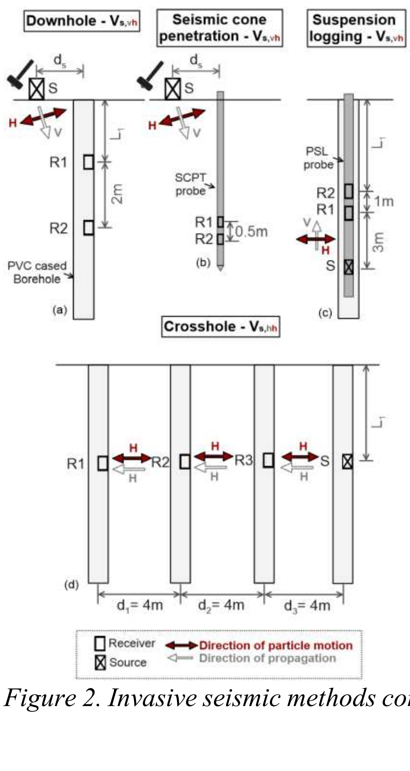

Figure 2. Invasive seismic methods considered in this study.

Cross-hole tests (CH) are conducted by placing a seismic source in one borehole and receiver(s) in another borehole(s). The PS Logging (PSL) probe consists of a seismic source together with hydrophone and geophone receivers within a single probe. The PSL system measures the compression wave velocity and formation shear-wave velocities of a portion of the soil or rock column around the borehole. PMTs determine stiffness and strength by measuring the pressure and displacement of an expanding membrane installed by self boring, placement in pre-bored holes or by pushing behind a CPT. In the laboratory, RC/BE and low-amplitude cyclic triaxial tests are performed on the high-quality samples.

3 KEY CHALLENGES

Measurements of V_s are known to be sensitive to the test procedure adopted including: (i) geophone arrays and spacing; (ii) source type, coupling and location (Koreta et al., 2022) and; (iii) testing mode e.g. DH/SCPT versus PSL, drilling versus seabed SCPT data acquisition Gibbs et al. (2018). The importance of targeting sampling frequency for a given receiver spacing is illustrated in Figure 3 for a V_s value of 450m/s (Rice, 1984). As the receiver spacing increases, the sampling frequency required to achieve a given level of accuracy in elapsed travel time, Δt, decreases which should be carefully considered when planning testing programmes.

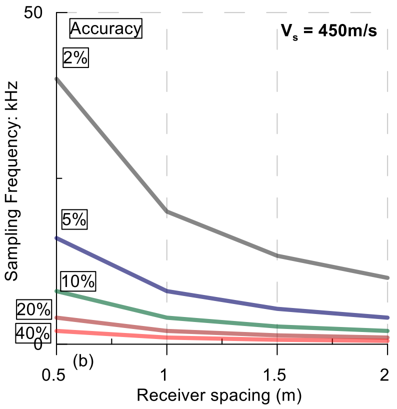

Figure 3. Relationship between sampling frequency, receiver spacing and accuracy in travel time estimation.

A comprehensive review of interpretation methods for downhole testing was provided by Stolte and Cox (2019). Classic approaches such as those that involve picking characteristic points on wave arrivals at sensors at different depths are prone to subjectivity and resist automation. The cross-correlation (CC) method (Campanella and Stewart, 1991) is often preferred where data quality allows, since it correlates information from the full signal and is less subjective to interpret. The method involves sliding one of the signals over a consecutive other signal recorded at a different depth and computing the similarity between the two signals at each time shift; CC was used for the majority of SOURCE interpretation. Once travel times have been evaluated, the analyst must make an assumption on ray path; inclined straight ray paths are typically assumed – with ray tracing based on Snell's law utilised for shallow layers and high stiffness contrasts.

Residual uncertainty in V_s due to poor data quality or ambiguous interpretation is rarely communicated to the end user of the data (Stolte and Cox 2019). There is no consensus yet on a consistent method to quantify epistemic or aleatory uncertainty. While the cross-correlation coefficient (CCC) is often used to quantify data quality, it is known to be unreliable since measurement noise is also correlated leading in some cases to unrepresentative high CCC values that can mislead investigators.

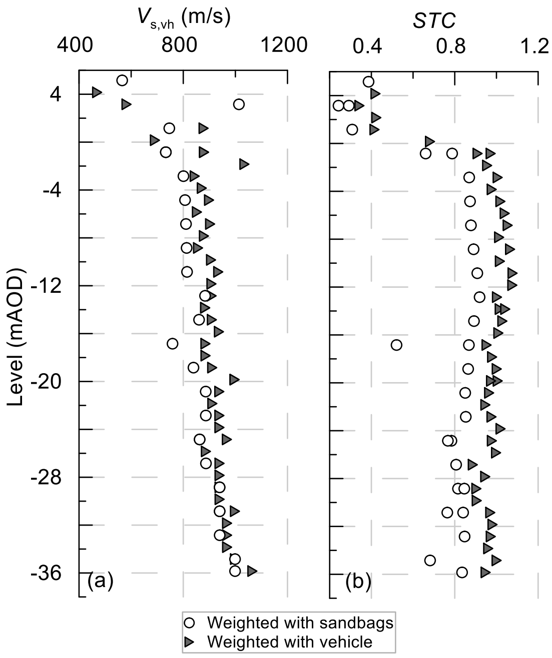

Figure 4. Influence of shear beam weighting on DH results.

Baziw and Verbeek (2017) proposed another approach: a data quality classification framework that combines CCCs with additional signal quality indicators related to linearity between receivers and the shape of the source input signal. The Seismic Trace Characterisation (STC) results in a numeric value between 0 (unacceptable) and 1 (excellent) that can be used to filter signals by flagging erroneous results and traces that require manual interpretation. Figure 4 demonstrates the usefulness of STC values when systematically assessing influence factors on (vertically propagating horizontally polarised) $V_{s,vh}$ obtained in DH testing at the chalk site. This particular excercise assessed the influence of shear beam weighting or ground coupling on the obtained measurements. The STCs were higher, and the data less scattered where the shear beam was weighted using a vehicle (11kN) compared to when it was weighted using sandbags (1.5kN). While STC appears to be a reliable indicator of data quality, the framework alone cannot capture the complete set of uncertainties present in the shear profile and additional developments are required.

4 SUMMARY & CONCLUSIONS

The SOURCE project aims to quantify and reduce the uncertainties associated with soil and rock in situ stiffness measurements to minimise the influence on offshore foundation design. Benchmark data sets are being collected at onshore sites in the UK and Europe with ground conditions relevant to offshore ground conditions. The fieldwork is providing new insights into in situ stiffness in these materials and facilitating the development of new analysis procedures. While the focus here is on offshore foundation design, the outcomes will be equally applicable to onshore soil structure interaction problems.

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