Using Sub-Bottom Imager data to interpret shallow soil conditions for use in offshore wind site characterisation.

Introduction

The characterisation of potentially problematic shallow soil conditions is vital in building an integrated ground model and defining the site investigation of an offshore wind farm. Problematic conditions such as hard stratums or subsea boulders can prove a real risk to the emplacement of infrastructure such as Wind Turbine Generator (WTG) foundations (Holeyman et al, 2015). In this case study, a windfarm developer was conducting piling operations at a site within the central North Sea. Suction piles, used to emplace WTG jackets, were refusing at a number of locations, with the refusal understood to be related to a problematic shallow soil unit – such as a high strength clay, dense sand or cobble/boulder layer.

This study outlines the process in which the Sub-Bottom Imager ™ (SBI) was used to interpret and map stratigraphic layers and discrete anomalies (buried boulders) at one such WTG site, in order to assist in informing the decision as where best locate the WTG jackets. The SBI from Kraken Robotics is a 3D acoustic data acquisition system used to detect and image objects in the sub-surface, most commonly linear and discrete objects such as cables, boulders and unexploded ordnance (UXO) but increasingly to interpret stratigraphic layers in shallow soils.

SBI Data Acquisition

The SBI consists of three acoustic chirp projectors and a 40-channel receiver array, alongside a coupled Inertial Navigation System (INS) and Doppler Velocity Log (DVL). As each individual chirp projector emits an acoustic signal, data is recorded simultaneously on all 40 channels within the array. The SBI was mounted to the base of a Work-Class Remotely Operated Vehicle (WROV) during the survey.

As the WROV moves forward, features in front of the array move into range and features behind the array move out of range, remaining illuminated for several seconds and detected from multiple aspects – 100 times or more (Dinn, 2012). As the SBI moves forward it builds a history of its previous positions, which are used to generate a Synthetic Aperture Sonar (SAS) array (Figure 1). Combined with accurate altitude tracking and positioning, a 3D volumetric swath is rendered, with a width of approximately 6 m at seabed and an average signal penetration of 5 m below seabed, depending on the shallow soil conditions.

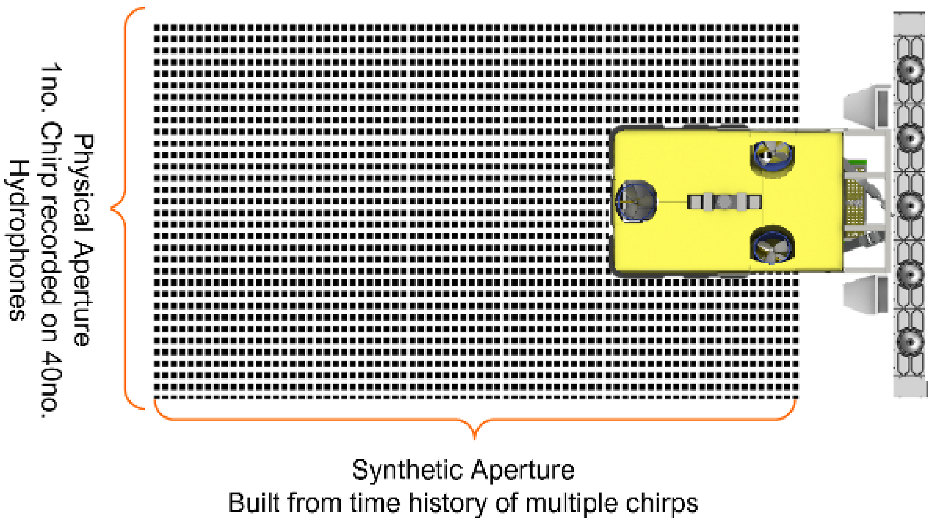

Figure 1 *Schematic showing SBI frame mounted to the base of the WROV with the difference between physical aperture and synthetic aperture generation highlighted.*

Survey Area and Geology

The survey area was situated within the central North Sea, at an approximate depth of 43.0 m below LAT. The survey area comprised a 150 m x 150 m survey grid around the primary WTG location.

Geotechnical data in the form of cone-penetration tests (CPT) were made available to Kraken Robotics. These showed a laterally continuous, loose to dense Holocene sand layer, overlying a medium dense to very dense sand. A thin (approx. 0.2 m) clay layer within this underlying sand was also identified within a single CPT location.

Methodology

An on-site calibration was performed using a surrogate object to confirm functionality of the SBI equipment and the positioning, precision, and the repeatability of results prior to the main survey commencing.

The SBI acquired 51 lines at 3 m line spacing, in order to acquire 200% coverage throughout the survey area. As discrete anomalies (buried boulders) were to be interpreted, 200% data coverage was beneficial to confirm repeatability and provide increased confidence with the interpretation. Each discrete anomaly was covered by at least two SBI 3D acoustic volumes.

The SBI was flown at an altitude of approximately 3.5 m above the seabed at a speed of 0.5 to 1.0 knot, typical for WROV surveys. The SBI data was rendered in the depth domain in real-time to 10 cm^3 voxels using a water and shallow soil velocity model derived during the calibration.

SBI Geophysical and Geotechnical Data Integration

The integration of SBI geophysical data with geotechnical data is fundamental to ground truthing the stratigraphic interpretation. Correlation between the SBI data and the CPT logs is conducted in a similar way to that of a conventional well-to-seismic tie when interpreting seismic data. That is, the position and depth of the CPT is plotted directly against the SBI data and the depth at which a change in geotechnical property occurs is referenced to that of a geophysical reflector, representing a change in acoustic impedance.

Interpretation of Stratigraphy and Discrete Anomalies

Shallow soil characteristics can be inferred by interpreting their acoustic signature. Relatively homogeneous shallow soil units, such as clays and well-sorted sands, where the density (sands/gravels) and strength (clays/silts) are similar throughout, are expected to have a low amplitude and featureless acoustic signature. Heterogeneous shallow soil units such as poorly sorted sands and interbedded units, where density and strength vary, typically have an acoustic signature that is either well layered or chaotic (Roksandic, M.). The amplitude of the acoustic impendence contrast also aids in interpretation, with high amplitude reflections implying a large change in density and/or strength of the sediments. Whereas low amplitude reflections, imply a small or gradual change between two stratigraphic units or density/strength changes within a shallow soil unit of the same lithology.

As boulders principally consist of consolidated or cemented rock mass, with a greater density compared to the surrounding sediment (Norbury, 2020), the diffractions caused by these features are expected to have a larger acoustic impedance, appearing as a discrete anomaly within the data. These are identified within an initial 3D volume of SBI data with the position then compared against an adjacent SBI 3D volume to check for repeatability. If the discrete anomaly is observed to repeat at the same location, the depth, length and width of the anomaly are measured as well as the anomalies relative amplitude and shape characteristics. Due to glacial processes that have affected the region, boulders are expected to be generally rounded or angular in shape and this can be observed in the SBI data. A confidence rank for each discrete anomaly is generated, using the aforementioned characteristics.

Results

The interpretation of discrete anomalies identified 101 buried boulders within the survey area such as seen in Figure 2a, with the majority of discrete anomalies located up to 1.0 m below seabed. The largest discrete anomaly had a length and width of 1.1 m and 0.7 m, respectively.

The stratigraphic interpretation showed the base of the Holocene to only be resolved in the north-east of the survey area. The Holocene sediments were shown to deepen to the east, to a maximum depth of over 3 m below seabed in the north-east of the survey area. Where the base of the Holocene sediments are resolved, it is observed as a strong acoustic, undulating reflector, indicating an unconformity, likely associated with Holocene transgressions (Gatliff et al, 1994). The acoustic character of the unit along with the geotechnical data indicate a coarse sand lithology. The presence of discontinuous reflectors, where the Holocene sediments are thicker, indicate possible lenses of denser sands and gravels, which aligns with both geotechnical data and background literature.

The primary unit interpreted was a thin high strength clay layer located within a medium dense to very dense sand unit underlying the Holocene sediments. The isopach of which is presented in Figure 3. This thin clay layer of approximate thickness of 0.2 m, was laterally continuous across the survey area, with the base, generally deepening from west to east, from a minimum depth below seabed of 0.5 m in the north-west to a maximum depth below seabed of 4.0 m in the north-east. The acoustic character of the sand unit shows a gradual change from a heterogenous shallow soil, containing laterally continuous reflectors to a more homogeneous unit. It should be noted that this change could also be affected by a reduction in acoustic signal when passing through a high strength clay layer. The unit shows to be more widespread than predicted by the geotechnical data, where it was only identified within one of the three CPT locations.

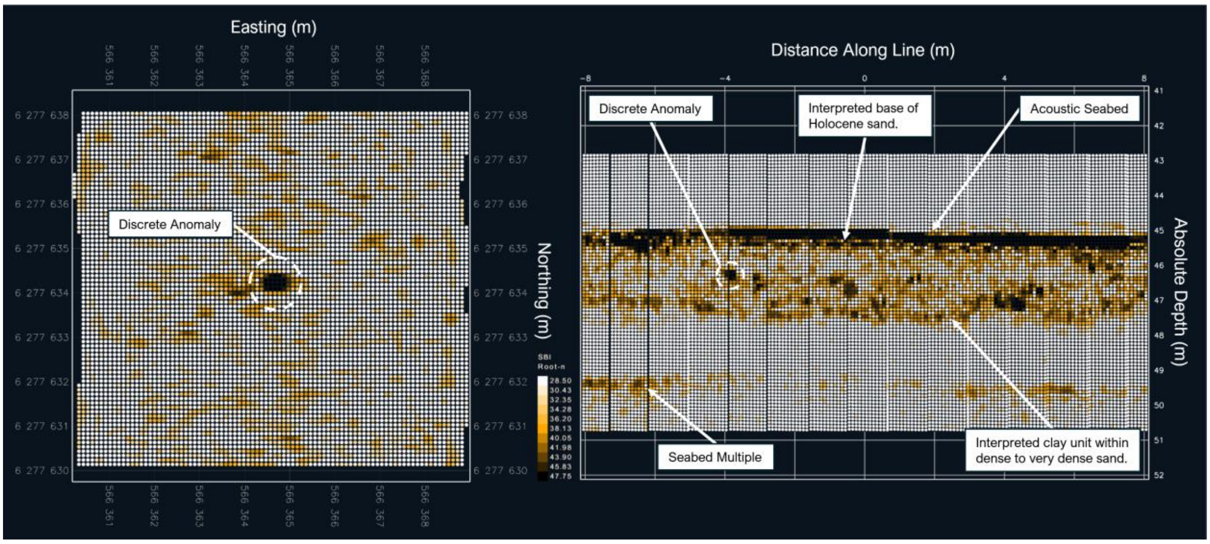

Figure 2a. (left) *Plan view image of an interpreted discrete anomaly.* ***Figure 2b. (right).*** *Profile view image showing the same discrete anomaly as well as both interpreted stratigraphic horizons.*

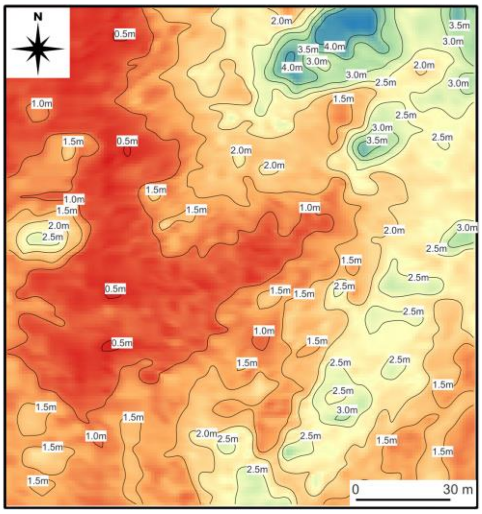

Figure 3 *Isopach map showing the extent and depth of the clay layer within the study area.*

Conclusions

Through ground-truthing the SBI data with geotechnical data, discrete anomalies as well as stratigraphic units were able to be mapped effectively across the study area. This included identifying the location and depth of potentially problematic sub-seabed boulders and shallow soils such as very dense sands or high strength clays. Moreover, the location and depth of boulders being assessed as to whether they are associated with stratigraphic units known to be glacial in origin such as drift deposits. These geohazards have the potential to hinder the emplacement of WTG foundations such as outlined in the report.

This enabled the client to supplement their integrated ground model and inform a decision in where best to locate the WTG foundations. The ability to map horizons in three dimensions across the survey area shows how using geotechnical point data alone can lead to uncertainty within the subsequent engineering analysis and can cause additional costs at a later stage in development.

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References

Holeyman, A., Peralta, P. and Charue, N. [2015] Boulder-Soil-Pile Dynamic Interaction, *Frontiers in Offshore Geotechnics III*.

Dinn, G. [2012] Field experience with a new sub-bottom investigation tool: Acoustic 3-D imaging of the sub-seabed, *2012 Oceans*, 1-9.

Gatliff, R W., Richards, P C., Smith, K., Graham, C C., McCormac, M., Smith, N J P., Long, D., Cameron, T D J., Evans, D., Stevenson, A G., Bulat, J., and Ritchie, J D. [1994] United Kingdom offshore regional report: the geology of the central North Sea. (London: HMSO for the British Geological Survey.).

Norbury, D [2020] *Soil and Rock Description in Engineering Practise*. 3rd Edition. Whittles Publishing, Caithness.

Roksandic, M., [2006]. Seismic facies analysis concepts. *Geophysical Prospecting*. **26**. 383-398.