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# Regional analysis of layered soils in the shallow subsurface across the North Sea for offshore cable burial

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**ABSTRACT:** Anchor-cable interactions account for 85 % of power cable failures. The planned rapid expansion of offshore wind in the UK will require new cable installations within busy shipping and fishing lanes. Therefore, it is essential that these are installed at an appropriate depth. The current industry adopted approach from the Carbon Trust (2015) is to bury subsea cables to depths that are typically <5 metres below seafloor (mbsf). However, this approach assumes single homogeneous soil conditions with little information on the response of soil layering and associated contrasting geotechnical properties between layers. Here we present the results of statistical analysis and preliminary geological domain mapping which demonstrate that "layered" soils are common across the North Sea. The results highlight the importance of updating current Cable Burial Risk Assessment (CBRA) approaches to include "layered" soils, and associated changes in geotechnical properties (e.g., strength and density) between single and layered soil units to ensure more accurate CBRAs prior to site-specific surveys. Regional mapping of layered soils will also greatly benefit decision-makers at an early stage in projects when assessing the hazards associated with the positioning of future subsea cable developments. Ultimately, the database developed in this project provides geotechnical examples that inform physical and numerical modelling, undertaken by the University of Dundee and Durham University respectively, to create a new Cone Penetration Test-based tool for better constraining Depth of Lowering as part of the EPSRC grant "Offshore Cable Burial: How deep is deep enough?".

**Keywords:** Subsea Cables; Cable Burial Risk Assessment; Ground Modelling, Offshore Wind

## 1 INTRODUCTION

It is estimated that around 85 % of all subsea cable faults are caused by fishing activity and ship anchor strike, incurring costs of ~£250 million in lost energy production over a three-year period (2014-2017) (Renewable UK, 2018). The most obvious and accepted means of mitigation against external risks to subsea cables is to route cables away from hazardous areas. However, due to the nature of such hazards and the necessity to avoid circuitous cable routes, it is often not possible to mitigate risks in this way. Where mitigation of the risk posed to a cable is not possible through total hazard avoidance, the most common risk mitigation measure is cable burial, typically to depths of <5 metres below seafloor (mbsf). Buried cables are offered protection from external threats by backfilling the trench into which a cable is laid, presenting a physical barrier between the cable and the seabed.

The current widely adopted approach for determining the burial depth of subsea cables by relevant industries in the North Sea, is the "Cable Burial Risk Assessment (CBRA) Methodology" published by the Carbon Trust in 2015. This approach defines a target "Depth of Lowering" (DOL) for cable burial based on soil type and geotechnical parameters, typically using open-source data at an early project stage, amongst other variables that include sediment mobility and the probability of anthropogenic threats. However, this approach only factors in single, homogenous soil units, and therefore does not consider the effects of layered soil profiles (where separate layers have contrasting geotechnical properties) and the resultant resistance to anchor strike or maximum anchor penetration depths (Haertsch & Knight, 2022). Additional analysis is then performed by consultancies once site-specific survey data becomes available later in the project life-cycle. Research into soil profiles that are more stratigraphically complex is supported by the Carbon Trust (2015), who have commented that the "industry as a whole would benefit from further research into anchor penetration in a range of seabed types" resulting in more accurate CBRAs at an earlier stage in the project.

The initial findings from the first work package of the EPSRC grant "Offshore Cable Burial: How deep is deep enough?" are detailed in Johnson et al., (2024) and Macdonald et al., (2023). The results clearly demonstrate that there is a high frequency of "layered" soil occurrences within typical cable burial depths across the entire UK North Sea. The most common soil layering combinations were also identified, providing a basis for physical and numerical modelling work.

Studies by Sharif et al., (2023) and Bird et al., (2023a, b) indicate that anchor penetration depth is highly dependent on the geotechnical properties of the soil, such as relative density and shear strength, highlighting, for example, that the current CBRA methodology underpredicts anchor penetration depth in "very loose to loose drained sand" conditions.

Johnson et al., (2024) also generated regional maps of the occurrence of different "problematic" soil units (that present challenges to cable installation) in shallow gravity cores and vibrocore samples, such as gravel and peat. Regional geospatial analyses of shallow soil conditions of this nature are potentially powerful decision-making tools for early-stage cable installation planning. Products derived from these analyses could act as baseline datasets allowing better optimisation of approaches to risk mitigation but would not replace a bespoke route-specific assessment. Here we present further analysis using the BGS Offshore Core database to demonstrate the value of regional analyses of layered soils that can be developed with stakeholder engagement.

## 2 METHODOLOGY

The offshore core database was compiled using scanned records from >13,000 sediment cores in the UK North Sea, obtained from the British Geological Survey (BGS) Offshore GeoIndex. This primarily comprised shallow gravity cores and vibrocores that penetrated to a maximum depth of 6 mbsf. Figure 1 shows the locations of core sites with usable data. The methodology used to create the offshore core database was previously described by Macdonald et al., (2023) and Johnson et al., (2024), and is briefly summarised below.

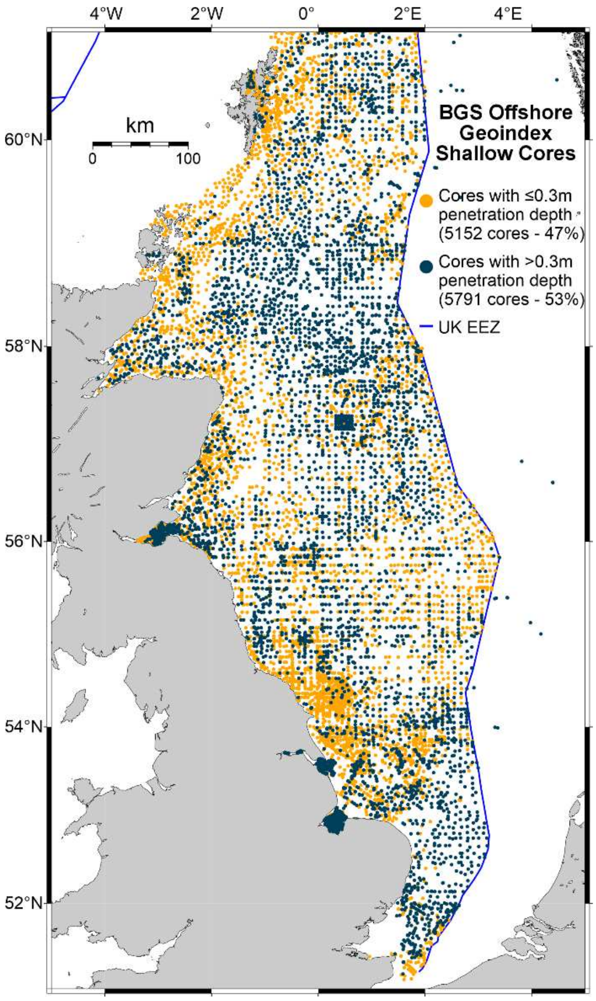


*Figure 1 - Map of filtered core data points for the North Sea study area. All data points extracted from the BGS Offshore Geoindex © 2024. Coastline data – GSHHG © 2024.*

For the initial work, the core database was filtered to exclude core records with inadequate or incomplete information. Sample records obtained from ≤0.3 mbsf were also removed following discussions with the project's industry steering group. This was due to a skewing effect whereby very shallow cores (<0.3 m) primarily sampled the mobile sediment layer, leading to spatial over-representation of "SAND" as a soil type. These cores are shown in yellow in Figure 1, whilst cores with >0.3 mbsf penetration are shown in blue. The collated and filtered database was statistically analysed for the frequency of the most common soil layering combinations.

For the new, preliminary, work on domain mapping presented in this paper, we filtered the database for cores with at least 2 mbsf penetration. This was done to capture sufficient data for reasonable geospatial coverage and avoid skewing issues, whilst also considering that most trenching contractors' market at least a minimum depth of 2 mbsf. The collated core database contains a wealth of qualitative lithological and geotechnical sample descriptions. Due to the significant time over which the core samples have been acquired (from the 1970s to present), the qualitative information has a lot of descriptive heterogeneity. However, we overcome this issue by categorisation of the cores into five (5) common soil profile domains based on the shallowest 2 mbsf. The domains were categorised using the main lithological and geotechnical terms: lithological [clay, silt, sand, gravel, bedrock, peat, boulders]; geotechnical [very soft, soft, firm, stiff, very stiff, hard, very loose, loose, medium dense, dense, very dense] and additional categories where appropriate. Each named and located core sample within the database may be made up of multiple samples (downhole, in-depth mbsf), tagged with bed-top depth, bed-base depth, standardised lithological descriptor and standardised geotechnical descriptor. The results of the initial mapping are presented in Figure 2 and discussed in Section 3.

# 3 RESULTS

## 3.1 BGS Soil Layering Combinations

### 3.1.1 ≥0.3 m penetration dataset

Initial statistical analysis of the filtered core database show that 48 % (2,946) of cores comprised only one proven soil unit, whilst 52 % (3,224) exhibited soil layering within the top 6 m. The breakdown of these "layered" cores is as follows: 40 % (2,466) have two (2) proven soil units, 10 % (592) have three (3), 2 % (117) have four (4) and <1 % (49) have greater than or equal to five (5) layers of proven soil units. However, although filtered for minimum penetration depth, the maximum penetration depth of cores within the database is highly variable.

Of the cores that have ≥0.3 mbsf penetration, 38 % (2346 of total cores) recovered lithological profiles of only homogeneous "SAND" (though note point above about variable penetration depths. The second most frequently recorded profile, 29 % (1762 cores) is a simple layered profile described as "SAND over CLAY". There are other instances of homogeneous profiles, for example where only "CLAY" is recovered, and more complex "layered" profiles, for example where more than two lithologies or more complex sequences of layers are recovered. Out of all of the profiles, "layered" soil profiles, which encompass all possible layering combinations, exceed "homogenous" soil profiles with 52 % of the cores recovering two or more layers.

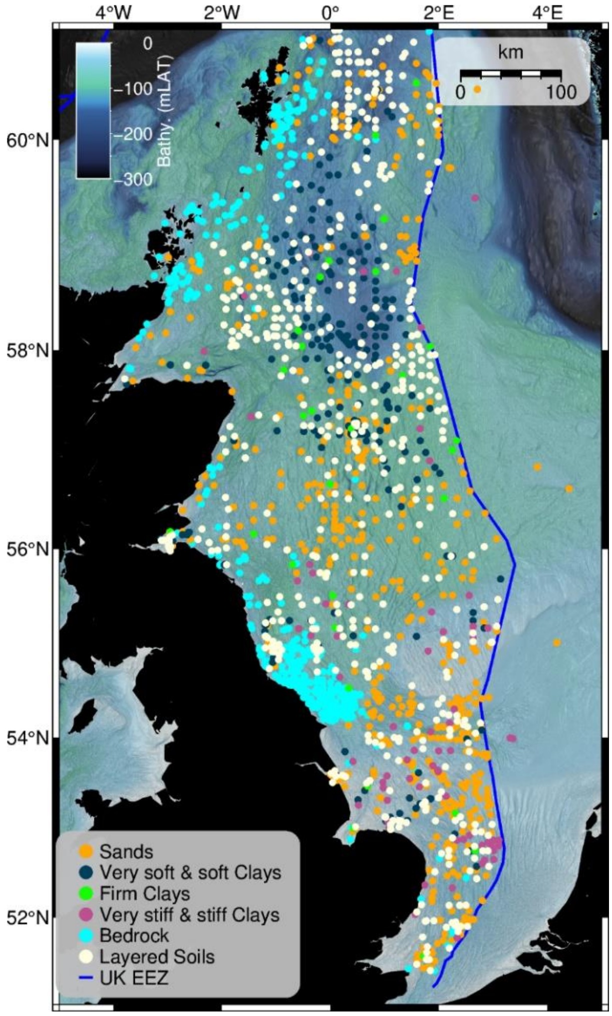


*Figure 2 - BGS Offshore shallow cores that have >2 mbsf penetration depth (1752 cores, ~16% of total cores), categorised into different soil profile domains. Bedrock domain shows cores with <2 mbsf penetration where bedrock is intercepted (669 cores, ~6% of total cores) (BGS © 2024). Coastline data – GSHHG © 2024; Bathymetry – EMODNet Digital Bathymetry (DTM 2022).*

### 3.1.2 Regional mapping

The offshore core database allowed generation of regional maps to showcase spatial trends in the dataset. Figure 2 presents an initial demonstration of the domains mapping approach discussed in Section 2, which categorised cores into 'homogenous' domains (i.e. sands; and very soft and soft; firm; and stiff and very stiff clays) versus a 'layered' domain (encompassing all possible layering combinations) and a shallow intercepts of 'bedrock' domain. With additional data and input from stakeholders, we will be able to define and differentiate the 'layered' domain into subclasses to suit their needs.

In addition, Figure 3 presents a new map which has been generated from the database as part of this study to show cores with bedrock intercepts within 2 mbsf depth. In total 669 cores encountered bedrock

<2 mbsf. Areas of shallow bedrock are typically avoided during cable routing and may require additional or remedial burial protection in areas along a cable route (DNV, 2021). As expected, cores with bedrock are dominant along the coastal sections of the North Sea meaning that they are more likely to impact nearshore and landfall sections of the cable routes. The extraction of this information from the core database also allows analysis of the spatial trends of bedrock lithology and correlation with other geological datasets for the North Sea (e.g., Chalk mapping off the coast of East Anglia, England; BGS, 2024).

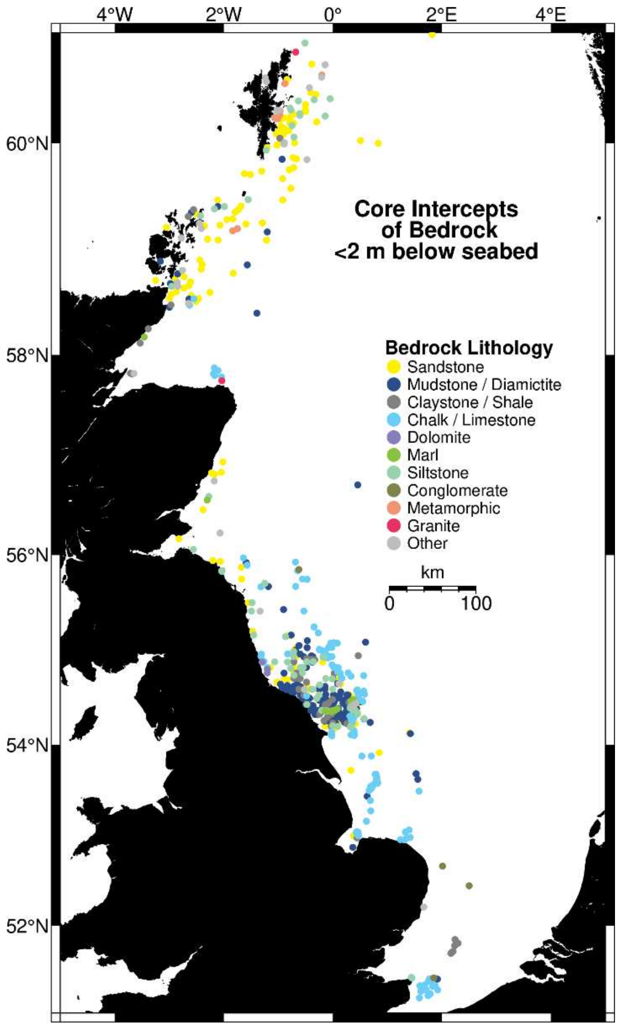


*Figure 3 - Map showing all cores with bedrock intercepts within 2 m depth of the seafloor (669 cores, ~6% of total cores). BGS © 2024. Coastline data – GSHHG © 2024.*

# 4 DISCUSSION

## 4.1 Mapping spatial trends in the North Sea

The offshore core database demonstrated that both “homogenous” and “layered” soil profiles are very common within the top 2 m across the North Sea study area. Figure 2 presents the spatial distribution of soil cores categorised into different soil profile domains (e.g., “very soft to soft clay” or “layered” soils). Of particular importance is understanding the variable distribution of shear strengths in “clay” soils. From the map in Figure 2, we observe “very soft to soft clays” are more broadly prevalent in the northern North Sea, particularly where the seabed is relatively deeper in the Witch Ground Basin offshore of NE Scotland. Conversely, “stiff to very-stiff clays” are more commonly found in the southern North Sea which may be related to the limits of the British and Irish Ice Sheet (see Dove et al., 2017). Future work will improve mapping of these spatial trends within the dataset by including geomorphological and geological datasets (such as the BGS Quaternary Deposits Summary Lithologies map) as well as further sub-divide the “Sand” and “Layered” domains.

It is important to note that the current approach of modelling a single “clay” unit with a uniform strength profile does not always reflect the data. Penetration depths can be heavily impacted by variable shear strength or relative density throughout a single “clay” or “sand” unit, respectively. Centrifuge experiments by Sharif et al., (2023) confirm that as the relative density of “sand” increases, the depth of anchor penetration decreases (from 2.5 fluke lengths in “loose sand”, to 0.4 fluke lengths in “dense sand”).

## 4.2 Implications of layered soils

Figure 4 displays a representative conceptual cross-section with example soil profiles extracted from geotechnical data from the Dogger Bank Offshore Wind Farm (OWF) in the North Sea. From approximately 180 cores analysed across the site, at least 20 different soil layering combinations were encountered within the top 2 m. This demonstrates the lateral and vertical variability of the ground conditions encountered within the zone of cable burial. The core profiles represent real examples of soil layering within potential cable burial depths. BH1038 on the left, and CPT1099 on the right are examples that fit within a dominant “homogenous” seabed description based solely on lithology. However, changes in geotechnical properties may be independent of the general lithology or lithological description within the trenching profile. In the case of these examples, both profiles exhibit downhole geotechnical properties variation despite their generalised lithological homogeneity, and so further analysis to model soil behaviour based on the density or strength profiles may be required during the DOL process. The example core profiles in the middle of the Figure 4 showcase two real examples of “layered” soil profiles from Dogger Bank. CPT1090 (middle left) encounters “1 m of dense SAND overlying a soft-to-very-stiff CLAY”, whilst BH1004 (middle right) encounters "0.2m of very-loose-to-loose-SAND overlying 0.6 m of very-soft CLAY overlying soft-to-very-stiff CLAY".

### 4.3 Data Limitations

Macdonald et al., (2024) highlighted several limitations associated with the BGS samples, and therefore within the core database. These mainly referred to the sample record age (approximately 1967-2015) and associated difficulties in the deciphering of the hand-written core logs. The penetration depth of the BGS samples also varied greatly due to the variation in acquisition rationale. In addition, geotechnical information (where recorded), was largely in the form of non-standardised qualitative descriptions rather than quantitative measurements.

## 5 CONCLUSIONS & NEXT STEPS

This study demonstrates that different "layered" soil profile domains can be mapped on a regional scale across the North Sea. As a minimum, CBRA methodologies should consider differentiating lithologies by stiffness or density, as well as consider a wider array of possible soil layering combinations, allowing more accurate CBRAs to be performed earlier in the cable-burial project life cycle. This paper presents the preliminary results, and so future work will refine the soil domains to consider the relative density of "sand" and different common "layered" soil profiles. From the collation of the lithological and geotechnical data we are in the process of constructing a toolbox to pull out the key attributes of soil profiles that are important to stakeholders in cable burial.

The next phase of the project will supplement the geotechnical data from other open-source datasets in a similar fashion to the BGS Offshore Core Database including data from The Crown Estate's Marine Data Exchange portal (MDE). This dataset, whilst more limited than the BGS database spatially, has two key advantages over the historical BGS cores: possible) and virtually all samples have at least qualitative description of undrained shear strength and relative density. In addition, these data will help to fill data gaps, and improve spatial resolution, particularly in the nearshore area along the east coast of England, where cable landfalls are common, as well as increasing the amount of qualitative and quantitative geotechnical data available. The results also demonstrate the power of the open-source datasets, such as those collated by BGS and MDE, to address the needs of the offshore cable burial industry.

Ultimately, the geospatial mapping of soil profile domains, combined with the experimental evidence and numerical modelling of anchor strike within the most representative soil profiles for cable burial can be used to generate enhanced risk maps, helping to optimise cable route planning and site investigation. Our work will also be used to inform the development of a new synthetic CPT tool, to inform a scientific, reliable and useable model for anchor penetration prediction (Robinson et al., 2021; Bird et al., 2023 a, b). Our results will help to better define likely CPT responses to real ground conditions, including the common layered soil combinations highlighted through this study.

## AUTHOR CONTRIBUTION STATEMENT

**CM**: Database construction, methodology and data analysis, writing, review, editing, conceptualisation. **DS**: Methodology and data analysis, writing, review, editing, conceptualisation. **RA:** Database construction, review, editing, conceptualisation. **GC**: Database construction, supervision, funding acquisition, review, editing, conceptualisation. **KJ:** Database construction, review, editing, conceptualisation. **WC**: Funding acquisition, review, editing, conceptualisation. **RB**: review, editing, conceptualisation. **CA**: Funding acquisition, review, editing, conceptualisation. **MB**: Funding acquisition, review, editing, conceptualisation. **YS**: review, editing, conceptualisation.

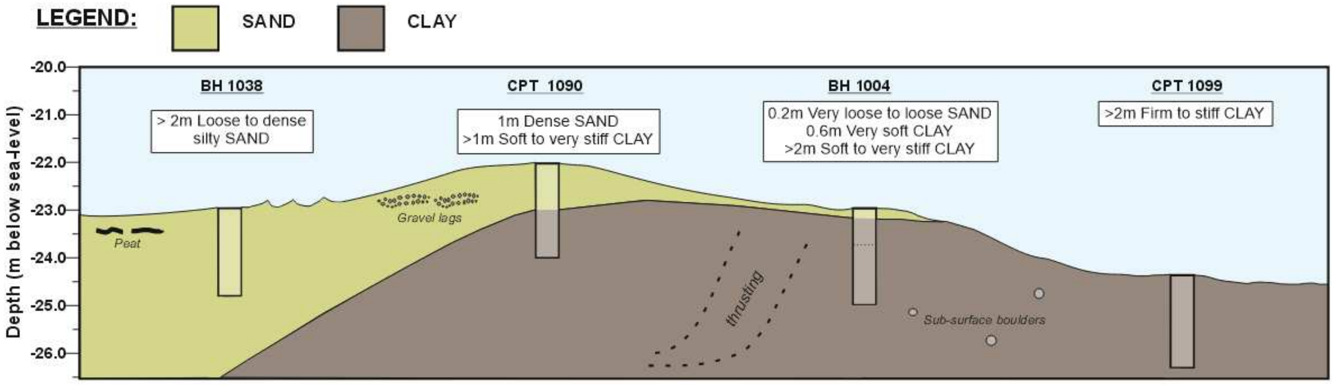


*Figure 4 – Conceptual cross-section showing four (4) example soil profiles from Dogger Bank OWF in the North Sea. Modified from Johnson et al., (2024). Cores profiles downloaded from MDE © 2024.*

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