Depth of Lowering and layered soils; a case study from across the North Sea.

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ABSTRACT: The Carbon Trust (2015) “Cable Burial Risk Assessment (CBRA) Methodology” document is widely used in the offshore subsea cable industry to define the cable burial Depth of Lowering (DoL). To-date published work on anchor penetration depths has focused on single homogeneous soil units, offering limited information on the response of different soil layering combinations, and associated contrasting geotechnical properties between soil units. By interrogating >11,000 shallow cores from the entire UK North Sea area, we demonstrate that “layered” soil combinations (e.g., “sand over clay”) are statistically common across the North Sea study area. The results also highlight the importance of updating current CBRA approaches to include “layered” soils, and associated changes in geotechnical properties (e.g., strength and density) between single and layered soil units. In addition, we collated geotechnical data for input into physical and numerical modelling undertaken by the University of Dundee and Durham University respectively (see Sharif et al., 2023; Bird et al., 2023 a, b), to assess the implications for the current CBRA Methodology. Ultimately the goal is to create a new CPT-based tool for better constraining the Depth of Lowering, as part of the EPSRC research grant “Offshore Cable Burial: How deep is deep enough?”.

1. Introduction

Offshore cable burial, via a variety of different trenching techniques (e.g., jet trenching, ploughing) is a common requirement for protection of cables across the telecommunications, renewable energy, and power interconnector cable industries. The planned rapid increase of offshore wind around the UK will require new cable installations in busy shipping and fishing routes, increasing the risk of anchor-cable interactions. Some cables, such as the Dogger Bank C export cable, span huge expanses of seafloor, often exceeding >200km. In addition, the introduction of floating wind technologies will eventually result in expansion into deeper waters farther from the UK coastline, requiring even longer cable routes to be planned. Therefore, it is essential that these new cables are installed at an appropriate depth to provide sufficient protection from cable hazards.

The current approach for determining the optimum Depth of Lowering (DoL) for cables is the “Cable Burial Risk Assessment (CBRA)” published by the Carbon Trust (2015). The approach is designed to be a repeatable process that considers several variables, including anchor size, fluke length and angle, and the soil type and properties, to define a target DoL. However, the CBRA approach focuses on single

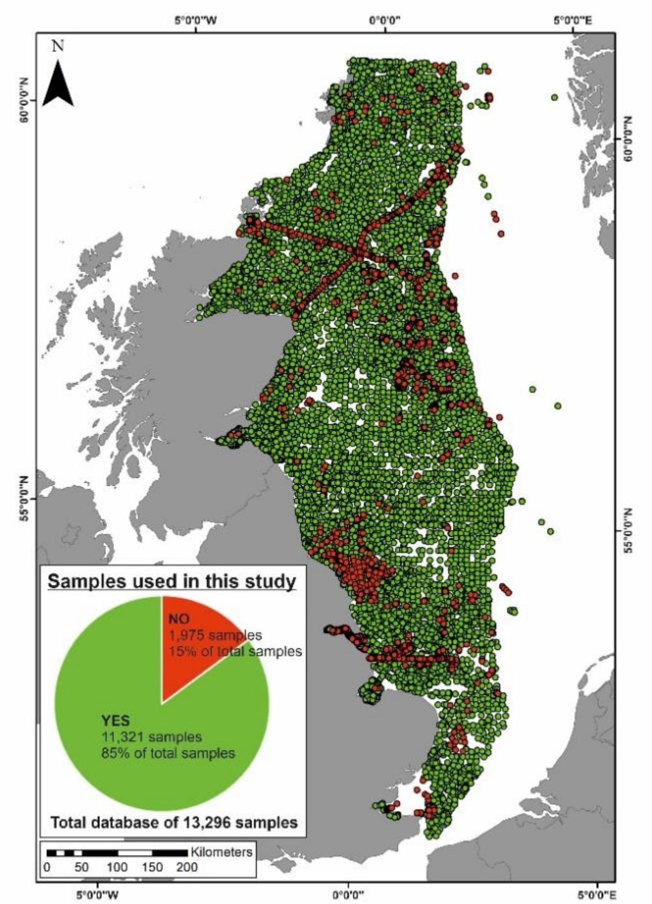


Figure 1: Map of >13,000 shallow core data points from the BGS Geoindex Offshore for the North Sea study area

homogenous soil units (sand and clay of varying densities and strengths, respectively), avoiding the effects of soil layering and associated contrasting geotechnical properties between soil units, on anchor penetration depths (Haertsch & Knight, 2022).

Project-specific evidence of layered soils within cable burial depths is often presented in commercial site investigation reports. To-date, as far as the authors are aware, no statistical study has been conducted into what the most common layered soil combinations are, and at present, the industry lacks appropriate tools to accurately determine anchor penetration depths in varying or complex soil conditions. Obtaining such data could provide valuable insight to inform future physical and numerical modelling of anchor penetration depths within these more stratigraphically complex soils. This is supported by the Carbon Trust (2015) who commented that the "*industry as a whole would benefit from further research into anchor penetration in a range of seabed types*".

In this paper, we present the results of a quantitative assessment based on an initial dataset of >11,000 cores, from the UK North Sea study area, to identify the statistically most common layered soil combinations across this area. Whilst this paper focuses on the presence of layered soils within the North Sea, preliminary work by Sharif et al., (2023) also investigates the effects of anchor penetration in sands with variable relative densities. Future work will seek to address the response of anchor penetration in different soil layering combinations with varying physical properties. This will be achieved by collating geotechnical site investigation data from across the North Sea to input into subsequent physical and numerical modelling by the University of Dundee and Durham University (see preliminary results by Sharif et al., 2023 and Bird et al., 2023).

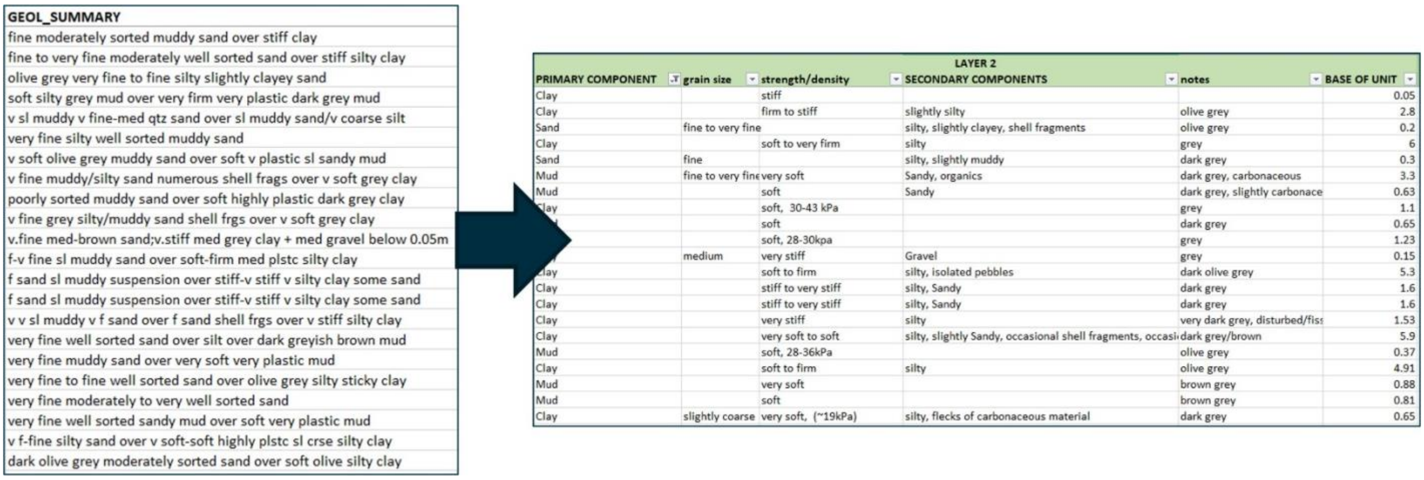
2. Methodology

The offshore core database was compiled using >13,000 cores, primarily shallow cores (gravity and vibrocore), from the British Geological Survey (BGS) GeoIndex Offshore for the UK North Sea. Figure 1 displays a map of all the available core data points for the North Sea study area.

An initial screening exercise was undertaken, to filter out cores with inadequate or incomplete information from the dataset. Out of the initial 13,296 cores, 11,321 cores (85%) were deemed suitable for use. The spread of the remaining cores is illustrated in green in Figure 1. The required data, such as the depths of tops/bottoms of soil units, was available in scanned handwritten core logs. Attempts to use Optical Character Recognition (OCR) software proved unsuccessful due to the variability in handwriting style and scan quality. Therefore, a laborious task of manually extracting these data was undertaken, resulting in the creation of a newly formatted offshore core (unitisation) database. From the database, we identified case study examples where different soil combinations are present in the North Sea for use in physical modelling tests, as described in Sharif et al., (2023).

An example extract from this unitisation database is shown in Figure 2. Individual soil layers were defined by depth to the base of the unit, using geological descriptions from the scanned core log sheets to identify the primary soil type (e.g., "SAND", "CLAY", etc.) of each layer. All soil descriptions were taken directly from the scanned core logs and no further interpretation has been completed for this study. Within the dataset, the maximum number of soil layers identified within a single core was six (6). Descriptions of grain size, secondary soil components (e.g., "muddy", "silty", etc.) and other additional information were also included. Where available, geotechnical parameters such as shear strength and relative density were included either as written observations or as measured digital values. Factual soil profiles and geotechnical parameters were extracted from the unitisation database as case study examples for this study, and in subsequent numerical and physical modelling work packages.

When considering maximum depth of interest for the database the Carbon Trust (2015) CBRA



GEOL_SUMMARY
fine moderately sorted muddy sand over stiff clay
fine to very fine moderately well sorted sand over stiff silty clay
olive grey very fine to fine silty slightly clayey sand
soft silty grey mud over very firm very plastic dark grey mud
v sl muddy v fine-med qtz sand over sl muddy sand/v coarse silt
very fine silty well sorted muddy sand
v soft olive grey muddy sand over soft v plastic sl sandy mud
v fine muddy/silty sand numerous shell frags over v soft grey clay
poorly sorted muddy sand over soft highly plastic dark grey clay
v fine grey silty/muddy sand shell frgs over v soft grey clay
v.fine med-brown sand;v.stiff med grey clay + med gravel below 0.05m
f-v fine sl muddy sand over soft-firm med plstc silty clay
f sand sl muddy suspension over stiff-v stiff v silty clay some sand
f sand sl muddy suspension over stiff-v stiff v silty clay some sand
v v sl muddy v f sand over f sand shell frgs over v stiff silty clay
very fine well sorted sand over silt over dark greyish brown mud
very fine muddy sand over very soft very plastic mud
very fine to fine well sorted sand over olive grey silty sticky clay
very fine moderately to very well sorted sand
very fine well sorted sandy mud over soft very plastic mud
v f-fine silty sand over v soft-soft highly plstc sl crse silty clay
dark olive grey moderately sorted sand over soft olive silty clay

LAYER 2					
PRIMARY COMPONENT	grain size	strength/density	SECONDARY COMPONENTS	notes	BASE OF UNIT
Clay		stiff			0.05
Clay		firm to stiff	slightly silty	olive grey	2.8
Sand	fine to very fine		silty, slightly clayey, shell fragments	olive grey	0.2
Clay		soft to very firm	silty	grey	6
Sand	fine		silty, slightly muddy	dark grey	0.3
Mud	fine to very fine	very soft	Sandy, organics	dark grey, carbonaceous	3.3
Mud		soft	Sandy	dark grey, slightly carbonace	0.63
Clay		soft, 30-43 kPa		grey	1.1
[illegible]		soft		dark grey	0.65
[illegible]		soft, 28-30kpa		grey	1.23
[illegible]	medium	very stiff	Gravel	grey	0.15
Clay		soft to firm	silty, isolated pebbles	dark olive grey	5.3
Clay		stiff to very stiff	silty, Sandy	dark grey	1.6
Clay		stiff to very stiff	silty, Sandy	dark grey	1.6
Clay		very stiff	silty	very dark grey, disturbed/fiss	1.53
Clay		very soft to soft	silty, slightly Sandy, occasional shell fragments, occasi	dark grey/brown	5.9
Mud		soft, 28-36kPa		olive grey	0.37
Clay		soft to firm	silty	olive grey	4.91
Mud		very soft		brown grey	0.88
Mud		soft		brown grey	0.81
Clay	slightly coarse	very soft, (~19kPa)	silty, flecks of carbonaceous material	dark grey	0.65

guidelines require the depth of route-specific geotechnical data (including PCPT and cores) to a nominal 5m depth. Due to the core barrel length of the equipment used for core recovery, a maximum recovery of 6m was achieved, and it was decided to include all data up to a maximum depth of 6 metres below seafloor (mbsf). However, we acknowledge that in practice target burial depths may be shallower than 6m.

Initial results from the final unitisation database (11,321 samples) are presented in Section 3.1. Through discussions with the industry steering group (see acknowledgements), it was noted that these initial results were skewed by cores with low penetration depths (e.g., 0.1-0.3m), as these effectively acted as grab samples and typically only recovered single soil units comprising surface sands. As a result, it was agreed that these low penetration cores (<0.3m) should be excluded at this stage of the study.

After applying the filters mentioned above, the remaining cores with >0.3m recovery accounted for 6,170 data entries. The results of the filtered dataset are presented in Section 3.2 and Section 3.3.

3. Soil Layering Combinations/Results

Once the data was collated, statistical plots were generated to demonstrate the most common soil layering combinations in the North Sea.

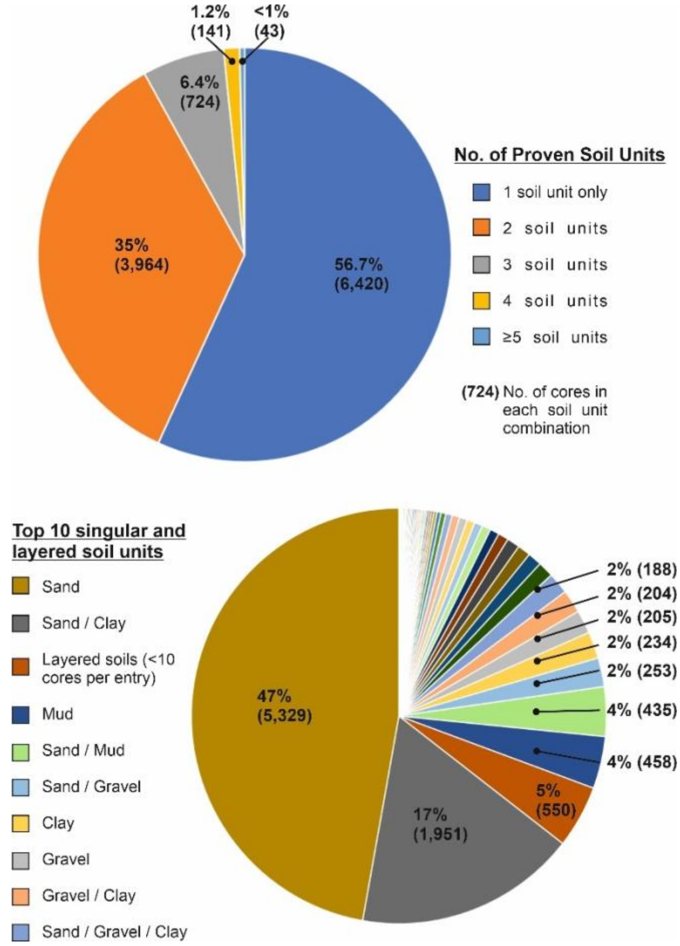
3.1. Results including shallow recovery core (0.0 – 6.0+m)

As previously detailed, the initial results from the unitisation database included all 11,321 cores deemed suitable for assessment. The results are presented in Figures 3 and 4 and are summarised below.

Using all available cores (11,321), cores exhibiting no layering at all account for 56.7% (6,420). Layered combinations, comprising two (2) to six (6) distinct soil units recorded within a single core, account for 43.3% (4,901) of the overall cores. Among the layered soil combinations, those with two (2) layers were the most common, with 3,964 (35%) of all cores falling into this category.

When considering the most common single and layered soil types and combinations, single “sand” profiles dominated the overall breakdown with 5,329 samples (47%). The second most common outcome, and the most common layered combination, was “sand over clay”, with 1,951 (17%) samples.

These results should be viewed as extremely conservative (in favor of single soil profiles) due to the inclusion of cores with poor (<0.3m) recovery, and tendency to skew results towards single layered soils typically of “sand” only. In addition, as discussed in Section 3.4, samples that record single “sand” only in cores of <0.3m recovery are registered as single/one (1) soil units at that location. In reality, there may be a second (or more) soil unit with a different soil composition within cable burial depths (e.g., clay at 0.5m) at that locality, but this is not captured due to the shallow recovery. Therefore, following discussions with the industry steering group (summarised in Section 2), it was decided to filter low penetration cores (<0.3m) out of the study).



The results of the “filtered” dataset are presented in Section 3.2 and Section 3.3.

Figure 3: Pie charts showing the number of proven soil units (i.e., one (1) to > five (5)) in all cores (top), and the top ten (10) singular and layered soil unit combinations for all cores in the North Sea study area (bottom)

3.2. Number of proven soil units (>0.3m core recovery)

Figure 4 displays the number of proven soil units within the “filtered” datasets (i.e., all cores with >0.3m recovery), up to a maximum of 6m penetration depth. Less than half of the cores (47.7%) showed no evidence of soil layering within the top 6m of stratigraphy. The remaining cores exhibited soil layering within the top 6m, with 40% displaying two (2) soil units, 9.6% displaying three (3) soil units, 1.9% displaying four (4) soil units and <1% displaying five (5) or six (6) soil units. These results demonstrate the influence of cores with <0.3m recovery on skewing the statistics towards one (1) single soil unit, with an ~9% reduction in number of cores recovering single homogeneous soil units compared to the results in Section 3.1 where 56.7% of cores were categorised as one (1) single soil unit).

As a result of excluding cores with poor (<0.3m) recovery, "layered" soil combinations become marginally dominant over "single" soil cores, with a difference of approximately ~5% (52.3% and 47.7% respectively).

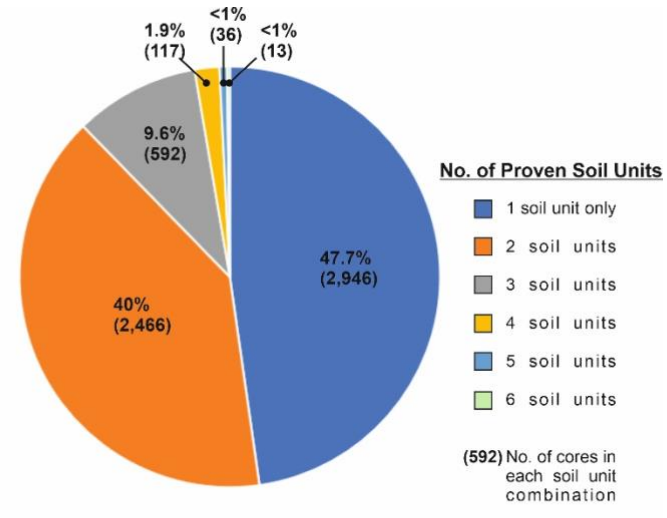


Figure 4: Pie chart showing the number of proven soil units (i.e., one (1) to six (6) in all cores with greater than 0.3m recovery.

3.3. *Common soil profiles (>0.3m recovery)*

Figure 5 presents the top ten (10) singular and layered soil combinations within the database. Single-unit soil profiles, comprising all "sand", all "mud", and all "clay" profiles, accounted for 46.1% of the most common soil combinations in the North Sea.

The remaining seven (7) entries in the top ten (10) combinations presented in Figure 4 consist of layered profiles with two (2) or more distinct soil units. Together, these seven (7) entries accounted for 38.9% of all recorded soil profiles in the North Sea. Therefore, the top ten (10) results listed in Figure 4 account for 85% of all singular and layered soil profiles recorded through this study.

Additionally, the top results for each soil layering combination (1-6 layers) are listed below along with number of cores and percentage within that layer combination. For example, out of all cores that contain a single (1) layer (i.e., 2,346 cores), 79.6% show an "all sand" profile, while out of all cores with four (4) layers (i.e., 23 cores), 19.7% show "sand over clay over sand over clay".

- Single (1) layer: Sand (2,346; 79.6%)
- Two (2) layers: Sand over clay (1,370; 55.6%)
- Three (3) layers: Sand over gravel over clay (171; 28.9%)
- Four (4) layers: Sand over clay over sand over clay (23; 19.7%)

The maximum number of cores recorded for a layered soil combination of five (5) or six (6) layers was three (3) and one (1) core, respectively. Due to the small number available, these were deemed insignificant to report in detail here. Other soil layer combinations, such as interbedded sands and clays, may also present significant problems for DoL assessments within the North Sea. However, although these cores were captured within the study, these soil combinations are only recorded in a handful of cores and are not considered to be statistically significant for this study.

Furthermore, several cores containing different lithified rock types (such as chalk, siltstone, mudstone, etc.) have been identified. Since the DoL assessment is based on unlithified soils, only the unlithified soil components from these cores were recorded in this study. For example, a core that records "sand over clay over mudstone" was recorded as two (2) soil units without including the bedrock component. Data from four (4) cores were discounted as they only recovered fragments of lithified rock (one (1) of mudstone, three (3) of siltstone) without any record of overlying unlithified soil components.

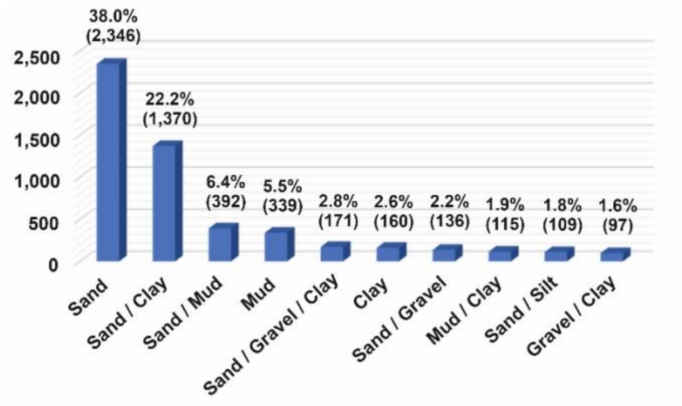


Figure 5: Graph displaying the top ten (10) singular and layered soil combinations (e.g., all "sand" or "sand over clay") in all cores greater than 0.3m penetration the North Sea

3.4. *Differential Penetration*

The results displayed in Figure 3, 4, & 5 indicate that single-unit soil profiles make up a significant number of cores across the North Sea. However, concerning soil layering, the results are likely to show overly conservative results with more cores exhibiting evidence of "layering" than what is estimated in the database. This is a consequence of the wide variation in the depth of available samples, with penetration depths and recovery, ranging from 0.3 m to 6+m. Therefore, shallow penetration cores may fail to penetrate soil layers that exist beneath the termination depth of the core. Figure 6 presents a schematic representation showing the effect of differential penetration observed in the current database. For instance, a core with one proven soil unit and limited to 0.3m recovery may record an all "sand" profile, and therefore, fail to penetrate the soil layering that may be present within target DoL. A core that terminates closer to the intended core termination depth of 6m, is much more likely to penetrate any soil layering that is present. To address the effects of differential penetration, only cores that achieved penetration depths of 5.0+m would need to be included. Since this would significantly limit the data available for this study, it has not been considered further in this paper but is presented in an open-access data report (Johnson et al., in prep).

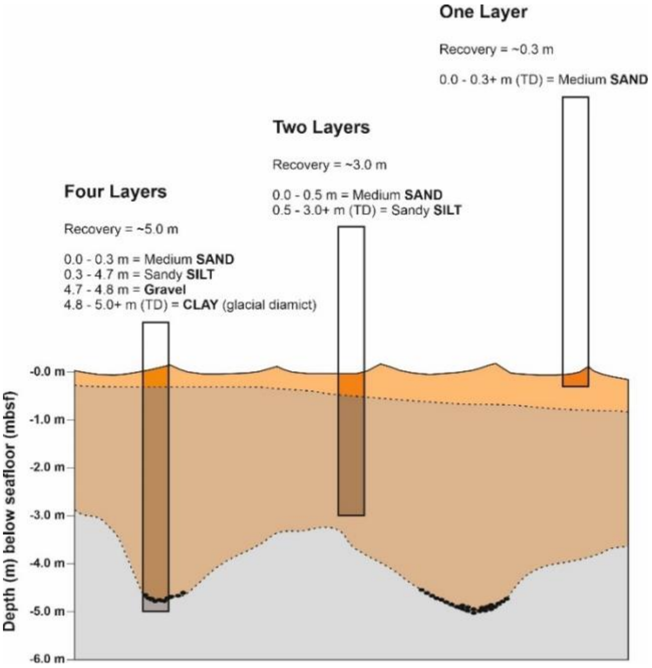


Figure 6: Schematic representation of the effect of differential core penetration within the current unitisation database

4. Discussion

The results, whilst not unexpected with respect to the Quaternary history of the United Kingdom Continental Shelf (UKCS), demonstrate that "layered" soil combinations are statistically common across the entire North Sea study area. In addition, the physical properties of both the "single" and "layered" soil unit combinations have been influenced by the Quaternary depositional history on the shallow subsurface and have the potential to significantly impact DoL assessments. Despite the predictability, these results are important as they explain the benefit of an update to the current approach to DoL assessments to include guidelines relating to more complex shallow ground conditions, going further than single homogeneous "sand" or "clay" units only.

4.1. Vertical and lateral variability in Quaternary soil units of the North Sea

The UKCS has experienced multiple glacial / interglacial periods throughout the Quaternary (2.58Ma to present day), which is reflected in the vertical and lateral variability of ground conditions within the shallow (<100m) subsurface. Across the North Sea, glacial to proglacial soil units can often comprise stiff to very stiff clay (till / glacial diamict) with abundant lithic gravel to boulder-sized clasts; well-sorted sands, silts and gravels comprising glacial outwash (sandur) deposits; interbedded sands, silts, gravels, and cobbles infilling discrete buried paleochannel systems; and rhythmically laminated clays and silts associated with proglacial lacustrine settings. Marine-terminating ice sheets have contributed to accumulations of glaciomarine deposits which can often comprise very soft to soft silts and clays. Conversely, due to reduced sea-levels, some areas of the North Sea were exposed as terrestrial settings (e.g., Dogger Bank) that have since been submerged. As a result, the shallow subsurface also contains evidence of a marine transgressive surface overlain with estuarine and coastal deposits including organic deposits such as fibrous peat (for example, see Emery et al., 2019) which can be challenging for trenching (Brown et al., 2015). Soil units associated with all the above depositional settings (and others that have not been listed) often vertically overlie one another, forming the complex shallow stratigraphy of the North Sea that is exemplified by the statistical results of this study.

To demonstrate the lateral and vertical variability of ground conditions encountered through this study and within cable burial depths (<6mbsf), Figure 7 shows an idealized, conceptual cross-section along a hypothetical subsea cable route. Although hypothetical, all samples were located within the southern North Sea. In addition, we acknowledge that target DoL is typically shallower than 6m. However, this depth was chosen due to the requirement from the Carbon Trust (2015) guidelines to record route-specific geotechnical data (including PCPT and cores) to a nominal 5m depth. This is discussed further in Section 2. The soil profiles and associated undrained shear strength (s_u) plots are factual examples extracted from the unitisation database compiled for this study. Undrained shear strength was chosen for this section as previous sensitivity analysis has suggested that, in clay, anchor penetration depths are very sensitive to undrained shear strength of the soil unit (Jones, 2018).

Core 54+2/183/VE/1 encounters "medium to fine grained SAND with abundant shell fragments" down to 0.88 m depth, which likely represents Holocene sand cover over the proposed cable route. From 0.88m to 1.06m, "brown coarse-grained sandy GRAVEL with abundant shell fragments and occasional cobbles" is recorded. This likely represents a gravel lag deposit, with the fine-grained fraction winnowed out through hydrodynamic processes, and the remaining coarse-grained gravels originating from the underlying soil unit. Gravel lag deposits of this nature are common across the North Sea, and wider North Atlantic Margin (e.g., Carr, 1999; Howe et al., 2001; Diesing et al., 2009). The final unit, from 1.06 m to the base of the core at 3.51m, comprises a "very stiff reddish brown silty sandy CLAY" which exhibits a relatively uniform (very high strength) undrained shear strength (s_u) profile of 172kPa to 197kPa. This unit likely represents a glacial diamict (till / boulder clay) with the strength profile reflecting the ice loading history of the soil unit. Comparable diamict/till units have been recorded elsewhere in the North Sea at or near seabed (<5.0mbsf), such as at Dogger Bank where they exhibit similarly overconsolidated profiles (Roberts et al., 2018).

Core 54+2/152/VE/1 contains the same stratigraphic units, but with the absence of the gravel lag unit and a thinner (0.3m thick) Holocene sand unit.

Core 54+1/120/VE/1 has "Holocene SAND" from 0.0m to 0.3m and then "glacial diamict / till (CLAY)" for the remainder of the core (3.80m). However, this example demonstrates how glacially deformed units, such as those that can be observed within thrust moraine complexes, can have very different and more complex S_u profiles with a wider scatter of S_u values due to thrusting, folding and incorporation of other soil packages with varying physical properties. In this example, undrained shear strength values can vary from medium (75kPa) to very high (180kPa) strength within a depth of 0.5m. This shows how modelling a single clay unit with a uniform strength profile does not always reflect real-world data and can cause challenges for assessing DoL given how sensitive anchor penetration depths are to S_u values.

Finally, core 54+2/121/VE/1 represents a change in depositional environment, passing laterally from the typically overconsolidated glacial soil units to soils that typify a lower energy depositional setting. Here, Holocene surface sands are replaced by "dark olive SILT" to a depth of 0.0m to 0.75m, with the remainder of the core (down to 5.20mbsf) comprising "silty CLAY with frequent fine sand laminae and occasional evidence of bioturbation". It is proposed that this soil unit, which exhibits extremely low (5kPa) to very low (14kPa) undrained shear strengths, represents a soil unit deposited under a glaciomarine environmental setting.

Whilst the cross-section shown in Figure 7 is hypothetical, the core data presented here are genuine examples that demonstrate 1) how the geological setting can influence layered soil combinations in the shallow (<6m) subsurface and 2) how the physical properties of these layered soil units (in this case, undrained shear strength) are intrinsically linked to depositional environment and historical stress regimes imposed upon the soils in question. It is these complexities throughout the soil profile that the current CBRA methodology, does not take into consideration, depending instead on a "dominant seabed" classification.

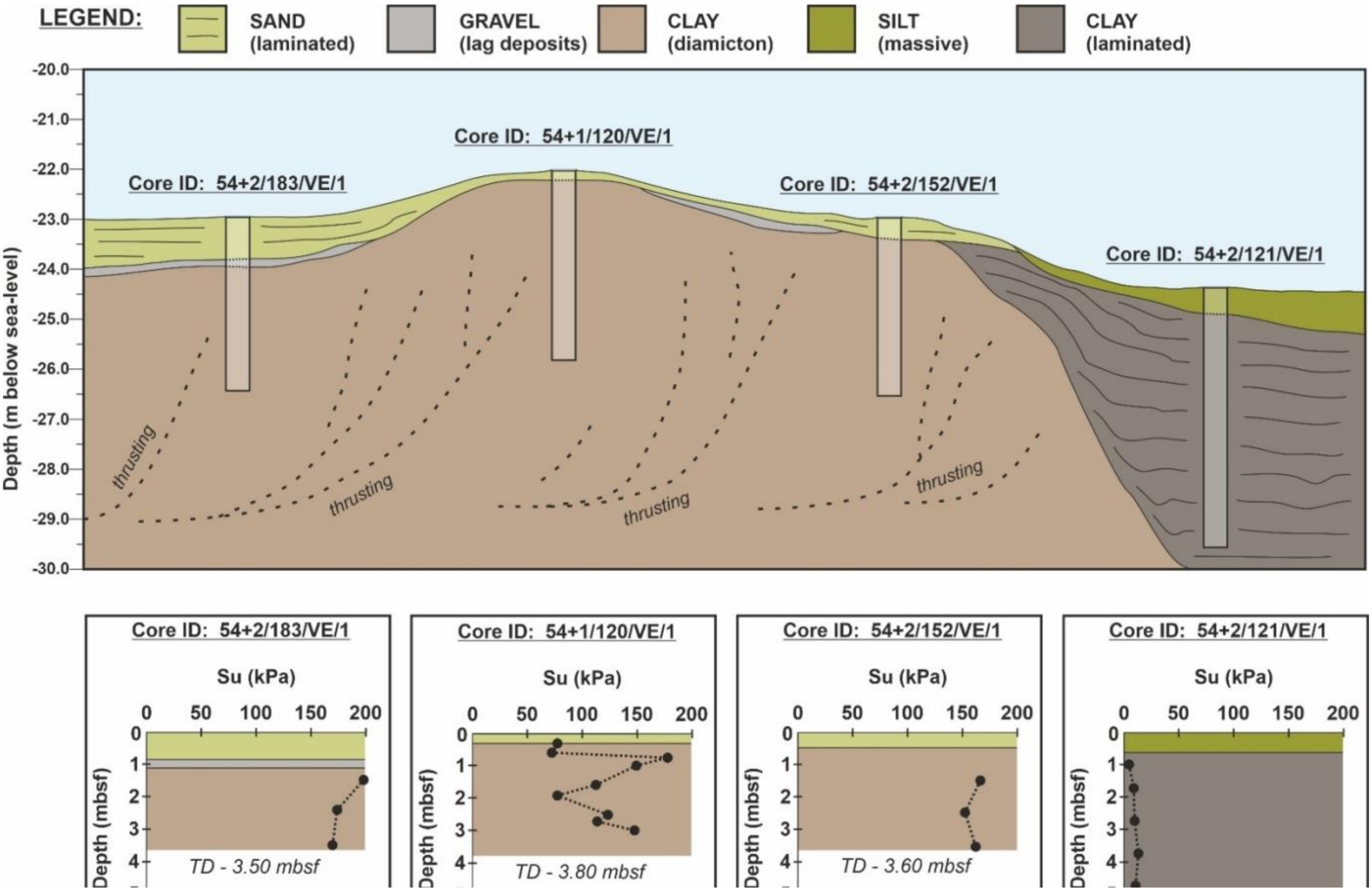


Figure 7: Idealised, conceptual cross-section along a hypothetical offshore cable route in the North Sea including example soil profiles and associated undrained shear strength plots (s_u) which have been extracted from the BGS offshore core database

4.2. *Implications of soil layering on cable burial*

Evidence of soil layering has been identified through this unitisation exercise. Soil layers have the potential to significantly impact DoL, particularly when present within the top 1m. Examples of soil layering combinations, and potential implications are discussed briefly here in reference to the four example profiles shown in Figure 7. The implications for cable burial are discussed in more detail in an open-access data report (Johnson et al., in prep).

Three (3) of the four (4) example cores in Figure 7 (i.e., 54+2/183/VE/1, 54+1/120/VE/1 and 54+2/152/VE/1) contain "stiff to hard (>75kPa) CLAY (or glacial diamict / till)" beneath a surficial SAND and/or GRAVEL layer within the top 1m. This combination at a shallow depth may limit DoL, depending on the chosen cable burial solution (such as when jet trenching in stiff CLAY and/or in GRAVEL), resulting in the risk of shallow burial along the cable route, and potentially exposing the asset to unnecessary risk of cable-anchor interactions.

Conversely, the presence of "very soft silty CLAY (<10 kPa)" at a shallow depth (i.e. <1m) in core 54+2/152/VE/1 may result in excessive anchor penetrations depths, meaning that the target DoL may not be economically or technically achievable with the depth (and trenching tool) required to protect it.

4.3. *Limitations*

The following limitations have been identified within the historical, scanned BGS samples themselves, and therefore within the unitisation database. They are as follows:

- The BGS core logs are scanned copies of hand-written, historical logs, ranging in age from 1967 to 2015, and so a degree of input error may occur due to the difficulty of deciphering products of this nature.
- Data standardisation is likely to have varied significantly over time with improvements in technology and scientific approaches.
- Numerical geotechnical values have been included where available, but more typically are recorded as descriptions or are in separate reports, which require further data mining.

4.4. *Current approaches and next steps*

At present, the existing guidance and methodologies for determining cable burial depths give anticipated anchor penetration depths based upon a "dominant seabed" classification. This provides different anchor fluke penetration ranges for different soil types with variable geotechnical parameters, although specific guidance is vague. However, the "dominant seabed" approach does not consider complex layered soils at shallow depths and does not factor in implications associated with changes in density/strength between various overlapping soil units (Haertsch & Knight, 2022).

This study has clearly shown that layered soils, and single soil units with variable geotechnical properties, are commonplace across the North Sea study area. Therefore, these different soil types and layer combinations warrant further study and should be considered in the DoL assessment. In addition, changes in physical properties (e.g., undrained shear strength) within a single soil unit are also not covered by the current DoL methodology. The results of centrifuge testing in different density sands by Sharif et al., (2023), show an underprediction of anchor penetration depth in very loose to loose drained sand conditions. In the future, we intend to consult other data repositories such as the Marine Data Exchange (MDE) to supplement the initial soil parameter dataset and provide additional case study examples to input into the subsequent work packages, including the addition of CPT data in layered and single soil unit profiles. This will provide valuable input into assessing the penetration depths of different anchor designs in other representative soil horizons from across the North Sea.

It is essential that any shallow subsurface model is based on the site investigation data available when planning cable burial depths. CPTs are considered to be the go-to site investigation data when developing a scientific, reliable and usable model for anchor penetration prediction (Robinson et al., 2021; Davidson et al., 2022; Bird et al., 2023 a, b). As a result, the statistical data generated through this preliminary assessment will be used to inform the development of a new CPT tool. This will specifically be designed to better define the depth of lowering based upon more accurate CPT response to actual ground conditions including the shallow soil layering combinations highlighted through this study, even when spaced at 1-2km intervals as per DNV (2016). Therefore, the outputs will then be used to develop a CPT-based anchor penetration tool for heterogeneous soil conditions and provide a pathway to integrate the tool into the probabilistic CBRA process.

5. Conclusions

Through interrogation of >11,000 shallow cores from the BGS GeoIndex Offshore, we demonstrate that "layered" soils are statistically common across the entire North Sea study area. Single cores, exhibiting no layering, account for approximately half of all cores in the database. This holds true both for the dataset containing all cores and the filtered dataset containing cores with >0.3m penetration (52.3% and 47.7% respectively). However, with removal of poor (<0.3m) recovery samples, "layered" soils become marginally dominant over single-unit soil profiles.

Within the filtered dataset, the top ten (10) most significant soil combinations make up 85% of all single-unit and layered soil profiles recorded in the North Sea study area. Of these top ten (10) combinations, single-unit soils (i.e., all “sand”, all “clay”, all “silt”) account for 46.1%, whilst “layered” soil combinations (e.g., “sand over clay”, “sand over gravel”, etc.) account for 38.9%.

Although these results are not surprising, they demonstrate that “layered” soil combinations in both single-unit and layered soil profiles, vary considerably throughout the North Sea. This variation is heavily influenced by the Quaternary depositional history on the shallow subsurface. Furthermore, these results highlight the need to update current CBRA approaches to include complex “layered” soils, and any associated changes in geotechnical properties (e.g., strength and density), in particular within the top 1m, as demonstrated by Sharif et al., (2023), between single and layered soil units.

Future work will continue to source and analyse the additional geotechnical data from across the North Sea to input into physical and numerical modelling. The outputs from the subsequent modelling work packages aim to ultimately create a new CPT-based tool for better constraining the DoL and probabilistic CBRA process.

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