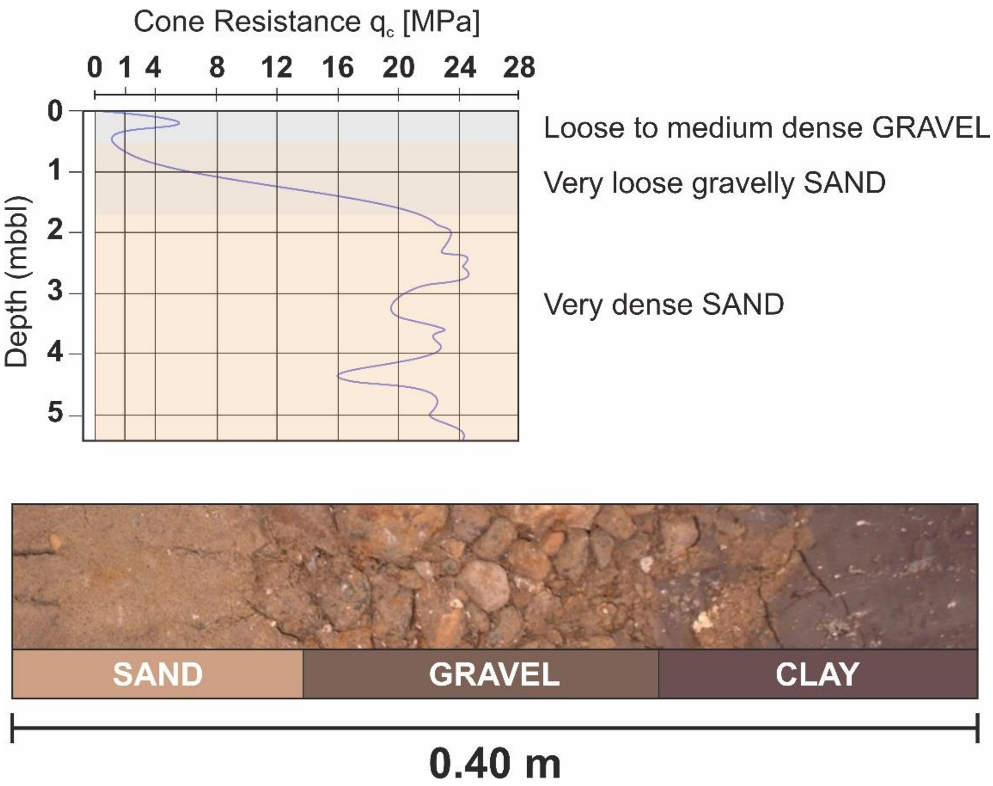
Layered Soils in the Shallow Subsurface (<6.0 m), North Sea; A Data Report

Marine Geoscience Programme

Open Report OR/24/031



BRITISH GEOLOGICAL SURVEY

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Layered Soils in the Shallow Subsurface (<6.0 m), North Sea; A Data Report

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Front cover

Example CPT profile through shallow sediments with a split BGS core image below.

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Foreword

This report is the published product of a study by the British Geological Survey (BGS), Durham University (DU) and University of Dundee (UoD). The research was funded by the Engineering and Physical Sciences Research Council (EPSRC) grant number EP/W000954/1, with the overall aim of answering the question “Offshore Cable Burial: How deep is deep enough?”. This report presents the results of Work Package 1 (WP1) which focuses on providing context for future work packages, by statistically assessing whether layered soils are a common occurrence within cable burial depths (<5 m below seabed) and, if so, what are the common layered soil combinations (e.g., sand over clay).

Acknowledgements

These results were generated through Work Package 1 (WP1) of the UKRI EPSRC grant EP/W000954/1 “Offshore Cable Burial: How deep is deep enough?”. Many thanks to our academic partners, Durham University and University of Dundee (individuals named under “Contributor/editor” on cover page), for advice and valuable input throughout this work package. Thanks to Professor David White (University of Southampton) for keeping this study focused through his role as Chair of the Industry Steering Group.

Many thanks to the industry partners who form the project steering group:

- Ørsted A/S
- Cathie Group
- Lloyd's Register Group Ltd.
- Global Marine Group
- The Crown Estate
- InterMoor (Bruce Anchor Ltd.)

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Summary

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 under-taken 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 DoL, as part of the EPSRC research grant “Offshore Cable Burial: How deep is deep enough?”.

1 Introduction

At present, the vast majority (>95%) of digital data traffic (e.g., emails, financial transactions) is transferred via a network of >400 subsea fibre-optic cables, spanning 1.8 million km across the ocean floor (Clare *et al*., 2023; Burnett & Carter, 2017; Carter *et al*., 2009). In addition, with the expansion of the offshore renewable energy sector, subsea power cables have become increasingly important in achieving NetZero targets as they allow ‘green energy’ to be transferred from offshore developments into the onshore national grid for the wider population to draw upon for domestic and industrial/business purposes. However, the security of these assets during their operational lifespan is not guaranteed and one of the main external threats comes from cable-anchor interactions. Of the 200-300 subsea cable faults that are reported per year, fishing and anchor interactions account for the vast majority, ~60% of reported faults with a further ~20% being classified as “unknown” (Clare *et al*., 2023; Carter *et al*., 2009). The current industry adopted approach to mitigating against this hazard is to bury subsea cables beneath the seafloor, typically in shallow depths of <5 m below seafloor (mbsf), with the rationale being that the soil cover (known as “backfill”) over the cable will restrict the vessel anchor from penetrating deep enough below the seabed and snagging on the cable.

Prior to cable trenching and burial works, it is necessary to calculate how deep an anchor may penetrate beneath the seabed based upon site-specific ground conditions for the cable corridor. Cable burial is a costly activity, and being overly conservative (i.e., burying all cables to an arbitrary, fixed depth) may not be necessary and will add costs to the overall project budget. However, on the other hand, burying a cable too shallow may not provide adequate soil cover to satisfy risk assessment criteria; for instance, shallow burial may not prevent anchor-cable interactions as the anchor may still be able to penetrate to the depth of the buried cable. At present, the offshore industry relies upon a binary approach to assessing anchor penetration depths, whereby the model utilises a single soil unit of either sand or clay composition. In some soil conditions, this approach can result in overly conservative (unnecessarily deep and costly) cable burial depths (Luger & Harkes, 2013). Conversely, it is clear from previous anchor-cable interactions, which are the dominate reason for subsea cable failures, that this approach can be under-conservative in other ground conditions.

An issue that is currently not addressed by the above approach is that of layered soil units (e.g., sand over gravel over clay) within the upper <5 mbsf, and how these might impact upon anchor penetration depths and cable burial depth calculations. However, at present, there is little/no statistical data in the public domain on common soil layering combinations at these depths, and likelihood of encountering layered soils if they are indeed common within burial depths.

1.1 AIMS OF WORK PACKAGE 1 (WP1), EPSRC GRANT EP/W000954/1, “OFFSHORE CABLE BURIAL: HOW DEEP IS DEEP ENOUGH?”,

Following the award of the Engineering & Physical Sciences Research Council (EPSRC) grant no. EP/W000954/1, for the project “Offshore Cable Burial: How deep is deep enough?”, the British Geological Survey (BGS) undertook an assessment of >13,000 archived sediment cores from across the entire North Sea, aiming to answer the following questions:

- Statistically, are stratigraphically layered soils common across the study area within cable burial depths (typically <5 mbsf)?
- If so, what are the most common soil layering combinations?
- Taking into consideration the current guidelines around Cable Burial Risk Assessment (CBRA), presented within a Carbon Trust (2015) report, is it enough to only consider homogeneous (single) soil units of either clay or sand when undertaking a Depth of Lowering (DoL) assessment?

These questions form the basis for Work Package 1 (WP1) of this 3-year project, which will inform subsequent work packages (physical and numerical/computational modelling led by University of Dundee and Durham University respectively) in an attempt to develop a new anchor penetration prediction tool to ultimately help the industry answer the question “how deep is deep enough?”.

1.2 CURRENT APPROACH TO DEPTH OF LOWERING (DOL) ASSESSMENT

Guidance on the current approach to DoL assessments are outlined by the Carbon Trust (2015). Here the Carbon Trust describe in 'Section 9.3: Anchor Penetration' that an assessment of seabed conditions along a cable route is an important part of the threat assessment. The suggested depth of anchor penetration, based upon US Naval Civil Engineering Laboratory (NCEL, 1987) is between 1 fluke lengths in sands and stiff clays, and between 3 to 5 fluke lengths in soft silts and clays (Carbon Trust, 2015). More recent anchor tests in the German Bight have also provided further insight into penetration depths in loose to dense sands, with findings suggesting that "the depth of influence is slightly less than the geometrically exposed fluke length" in granular soils (Carbon Trust, 2015; Maushake, 2013).

A worked example of the CBRA process, Appendix B within the Carbon Trust (2015) report, provides a clear snapshot of how the DoL assessment is undertaken at present. In this example, anchor penetration depths are estimated to be 1x fluke length for sands and stiff clays, and 3x fluke length for soft clays, with this penetration factor being taken from Shapiro (1997). In this worked example, a single dominant "Shallow Geology" type/profile is selected between the "Kilometre Points (KPs)" along the cable route, e.g., "Loose SAND", "Soft CLAY", "Firm CLAY", and "Loose SAND with megaripples present".

However, the above worked example and overall guidance document relies on tests and studies that have focused on single (homogeneous) soil profiles of typically either granular (sand) or cohesive (clay) soils, and no guidance is provided as to how layered (heterogeneous) soil profiles impact upon anchor penetration depths. The worked example, Appendix B, detailed above acknowledges that "the presence of layered or mixed sediments also represent complex conditions that require site specific assessment and engineering judgement" but provides no further guidance or recommendations on an industry standard approach to assessing a DoL for these complex soil profiles.

This is further complicated when considering the physical properties of shallow soil units. For instance, in geotechnical terms a single clay or sand profile may show significant heterogeneity in undrained shear strength (S_u) or relatively density (D_r) values respectively. At present, this aspect is largely absent in current guidance and best practice documents (e.g., Carbon Trust, 2015). And finally, in a more general sense, the authors of the Carbon Trust (2015) report highlight the necessity for further research into the topic of anchor penetration depths in a wider variety of ground conditions:

"Whilst individual developers have carried out project specific anchor penetration studies, industry as a whole would benefit from further research into anchor penetration in a range of seabed types" (Carbon Trust, 2015).

As a result, this open report summarises the high-level findings from the first Work Package (WP1) of an EPSRC-funded study designed to answer many of these open questions. Specifically, WP1 set out to answer the question relating to more complex, layered soil profiles within typical cable burial depths; based upon a comprehensive database, are homogeneous (single) or heterogeneous (layered) soil profiles more dominant for the study area (North Sea) and, if layered soil profiles are prevalent, what are the most common layered soil combinations upon which future studies (physical and computational modelling) can be based?

2 Methodology

13,296 shallow core (gravity and vibrocore) data points from the British Geological Survey (BGS) GeoIndex offshore for the UK North Sea were initially assessed for their availability and suitability to be used in the study. From this initial >13,000 cores, 1,975 were found to be either held in commercial confidence or unusable due to poor data quality and/or incomplete data entries, leaving 11,321 cores available for the study (**Figure 1**). Through the course of the analysis, a further 26 cores were discounted as, despite containing complete data entries, the values entered by hand were noted to be illegible. This left a final, usable dataset of 11,295 sediment cores.

Although some data pertaining to stratigraphic layering within the cores had been extracted previously for the BGS Offshore GeoIndex, this often-omitted crucial data such as base of soil units (mbsf) and soil unit thickness (m) data. These data were stored in scanned handwritten core logs and following unsuccessful attempts to use Optical Character Recognition (OCR) software, the logs were manually extracted into an offshore core (unitisation) database which was used as the basis for this study.

An example of the workflow of digitising the core logs and transferring the data into a more usable unitisation format is shown in **Figure 2**.

It was agreed upfront, between the project team and the Industry Steering Group, that grab samples, which typically have recovery/penetration depths of ≤0.2 mbsf, would be excluded from the study as they only capture the uppermost, seabed surface layer of soil and may be highly disturbed.

Upon further examination, it was observed that low penetration rates during coring resulted in 5,125 core samples with <0.3 m recovery below seabed. During preliminary assessments it was noted that, similar to grab samples, these shallow penetration cores had a tendency to heavily skew the statistics towards single (homogeneous) sand soil profiles as they generally only captured the 'seabed' soil unit (i.e., the single uppermost soil layer).

During discussions with project partners and the industry steering group it was agreed that it would be beneficial to the WP1 aims & objectives to analyse a subset of data that excluded cores with <0.3 m penetration. Further to this discussion, it was agreed that three subsets would be assessed separately by the BGS; one with all datapoints included (11,295 cores), one focussing on samples with ≥0.3 m penetration (6,170 cores) and one focussing on samples with ≥5.0 m penetration (467 cores). The reasoning behind a study focussing on samples with ≥5.0 m recovery was to have a subset of data that more rigidly adhered to the Carbon Trust (2015) CBRA guidelines which states that the depth of route-specific geotechnical data should be down to a nominal 5.0 mbsf depth.

2.1 SOIL DEFINITIONS

Table 1 defines the soil classification systems used to distinguish between different grain sizes and describe core samples. We were unable to differentiate where certain systems were used in the various logs, but there is typically very little difference in mm diameter between the classifications.

The soil classifications included in this report used the following systems:

- BS5930 (1999, 2015, 2020)
- Folk's classification (Folk 1954, Long 2006)

For clarity, we define peat and mud as the following:

Peat: a soil primarily composed of plant matter. BS5930: 1999, 2015 – peats are soils comprising predominantly organic materials (principally plant remains).

Mud: Defined by Folk (1954) as the silt and clay portion of a sample (**Table 1**). This is a generalised term, however due to the nature of the handwritten logs and lack of particle size analysis data (PSA, often referred to as the D percentile in geotechnical terms), we are unable to differentiate between silt and clay where mud is recorded.

2.2 LIMITATIONS

Several limitations must be considered when analysing the data stored in this database. First is the age of the dataset. Datapoints included range from the 1960's through to the 2010's. Given that the first (and sometimes only) layer of soil encountered during sampling may be sand, the thickness of this layer can be greatly impacted through sediment mobility over the years and decades, either reducing or increasing in thickness.

Core penetration depths can vary greatly, from <0.1 m to ~6.0 m, with 11 cores that are >6.2 m (this can happen when gassy soils expand slightly upon recovery, resulting in recovery length slightly exceeding the full barrel length). This bias is heavily influenced by the coring equipment used for the majority of this dataset which typically had maximum penetration depths / barrel lengths of ~6.0 m.

There is a lack of geotechnical data in certain areas, in some cases where BGS have more modern core records, these datasets are restricted due to commercial sensitivity. This report relies more heavily on field hand tests (Section 3.5), and there is currently a notable absence of publicly available relative density data for non-cohesive soils.

As mentioned previously, there is the "low penetration problem", whereby a large proportion of the useable cores are limited to <0.3 m penetration (a total of 5,125 cores, roughly 45% of the total cores available for use). These cores heavily skew the data towards single soil units comprising sand. In order to counter this, we include in this report a subset of data focussing on cores with ≥0.3 m penetration only (Section 3.2).

As mentioned in Section 2.1, the BGS core logs are scanned copies of hand-written historical logs, which range in age from 1967 to 2015, and have used a number of different soil classifications which have been developed and adjusted over the decades (**Table 1**). Therefore, a degree of input error may occur due to both the difficulty of reading the scanned logs, and assumptions made relating to grain size of soils logged. Further to this, data standardisation will most likely have varied over time with improvements to technology and new methodologies established regarding scientific approaches and logging techniques.

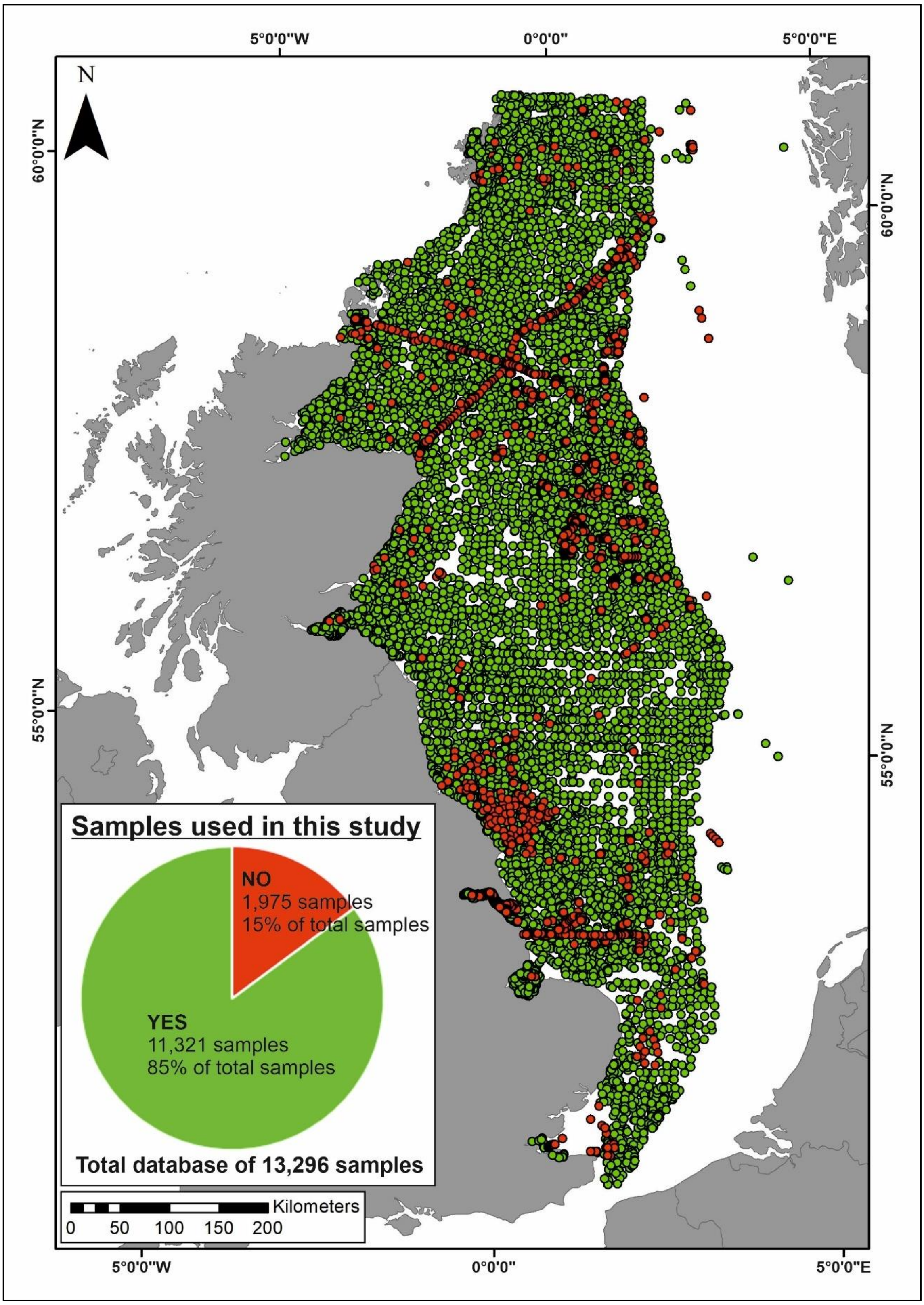
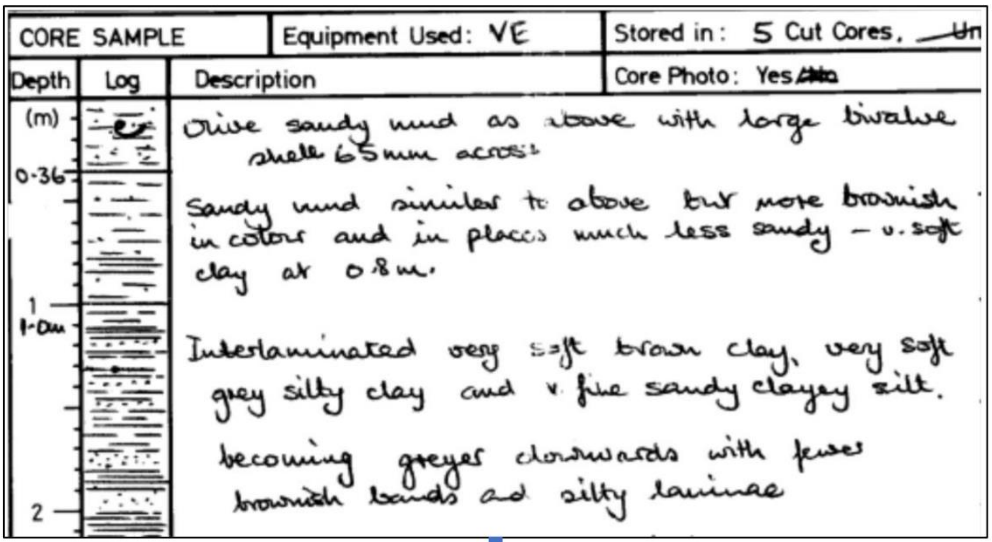


Figure 1: Map showing location of cores from the BGS Offshore GeoIndex that were assessed for use in this study. Datapoints in green are cores that were used for the study (11,321 samples). Datapoints in red are cores that were excluded from the study, most commonly due to commercially sensitive data (1,975 samples). Contains OS data © Crown copyright and database rights 2024.



GEOL_SUMMARY
muddy sand on sandy mud on brown mud sand on shelly sand on stiff mud
v soft sandy mud on col-banded grey/brown clay on stiff green clay
soft sticky mud shell frgs over red dry compact silty clay rock frags
fine grey soft mud/muddy silt over sticky clay over pebbly silty clay
fine grey soft mud/muddy silt over sticky clay over pebbly silty clay
olive foram rich silty mud on black streaked soft sl silty grey mud
SFT PLA FSNDY MUD 0.1/MDY FMSAND 0.5/TILL 2.4/SAND 2.5/TILL 2.6+ (Q)
MUD ON SILT/V FINE SAND ON MUDDY SAND/SANDY MUD ON M C SAND 4.9+ (Q)

LAYER 1 (seabed layer)					
PRIMARY COMPONENT	grain size	strength/density	SECONDARY COMPONENTS	notes	BASE OF UNIT
Mud	very fine	very soft	trace shell fragments	olive green	0.7
Mud	very fine to fine	very soft	Sandy, some rock fragments, shell	olive	0.36
Mud		soft		black	0.75
Mud	fine	soft		grey	0.05
Mud	fine	soft		grey	0.05
Mud		very soft	silty, Sandy	olive	0.11
Mud	very fine to	soft	lithic fragments (30%),	dark olive	0.1

Figure 2: Example of log digitisation progression from hand-written sedimentological log to tabulated unitisation format.

		British Soil Classification System	BS 5930:1999	Folk's classification (1954)
		BS 5930: 1981	BS 5930: 2015	Long (2006)
		mm diameter		
Boulders		>200	>200	n/a
Cobbles		60 - 200	63 - 200	
Gravel	Coarse	20 - 60	20 - 63	Gravel: >2
	Medium	6 - 20	6.3 - 20	
	Fine	2 - 6	2 - 6.3	
Sand	Coarse	0.6 - 2.0	0.63 - 2	Sand: 0.0625 - 2
	Medium	0.2 - 0.6	0.2 - 0.63	
	Fine	0.06 - 0.2	0.063 - 0.2	
Silt	Coarse	0.02 - 0.06	0.02 - 0.063	Mud (Clay and Silt): <0.0625
	Medium	0.006 - 0.02	0.0063 - 0.02	
	Fine	0.002 - 0.006	0.002 - 0.0063	
Clay		<0.002	<0.002	

Table 1: Soil classification systems (geotechnical engineering and sedimentological) used to describe core samples logged and used as the basis for this study.

3 Results

The following section breaks down the results from a number of filtered datasets, including the full BGS archive dataset, cores that sample greater or equal to 0.3 m below seafloor, cores that sample greater or equal to 5.0 m below seafloor (**Figure 3**). An additional, secondary objective of this study was to identify potentially problematic soils for cable trenching/burial operations. This was included in subsection 3.4 and includes instances of fibrous soils (peat) and gravel rich layers encountered in the database. Geotechnical considerations are briefly touched up in subsection 4.1.

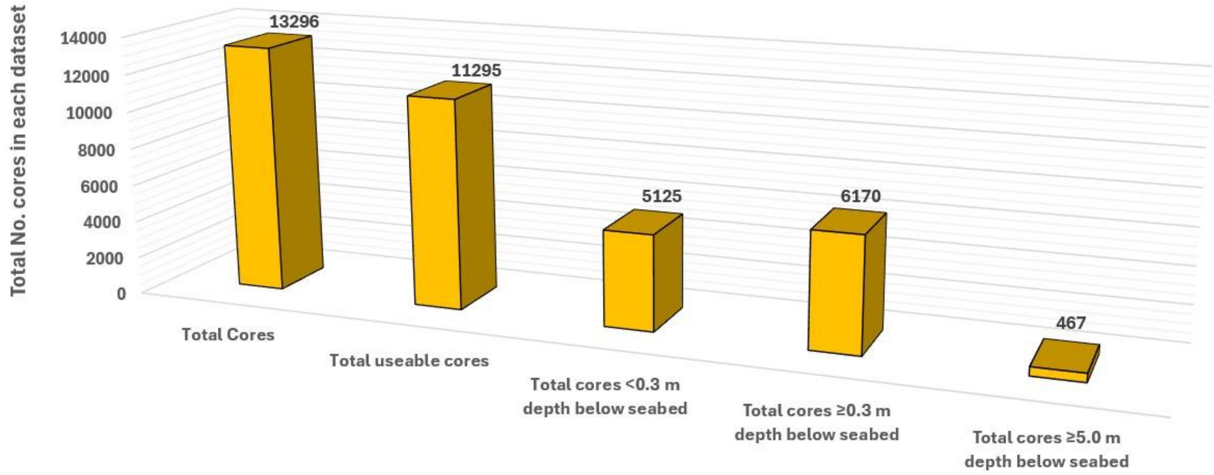


Figure 3: Histogram of total number of cores included in each major dataset described in “Section 3: Results”.

3.1 FULL BGS ARCHIVE DATASET

Results from the full BGS archive dataset (excluding confidential datasets) of 11,295 cores are summarised in this section. The results from this full dataset show 56.9% (6,426) of cores comprise only one proven soil unit (have just one layer). Following this, the next most common number of layered soils was two proven soil units (34.9%, or 3,945 of the cores). The total number of cores with three layers was 735 (6.5%), and four layers was 135 cores (1.2%). Lastly, the total number of cores with greater than or equal to five layers of proven soil units was 54 (<1%) (**Figure 4**).

Figure 5 shows the breakdown of total number of samples (and relevant percentages) of both singular and layered soil unit types. By far the most predominant soil type encountered is single layered SAND (5,329 cores, 47%). It should be noted that a limitation of this dataset is that these samples include cores that may only have sampled very shallow surface sediments (≤0.3 m depth), and as such may not accurately represent soil conditions, instead skewing the results towards single layered soils. The second most common soil layering type encountered is SAND over CLAY (1,951 cores, 17%). Included in this figure are the total number of layered soil types which have less than 10 cores per entry (550 cores total, 5%).

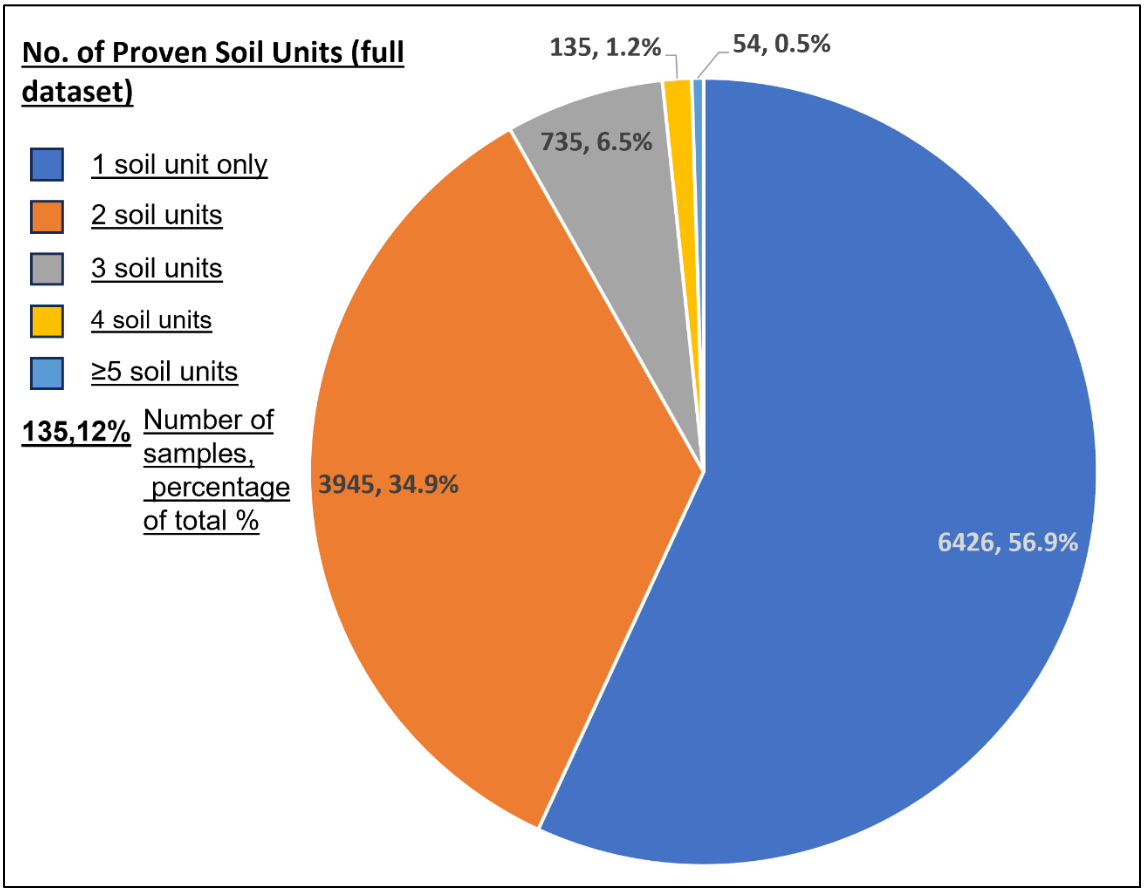


Figure 4 Pie chart showing the number of proven soil units (1 to ≥5 soil units) in all cores across the North Sea study area.

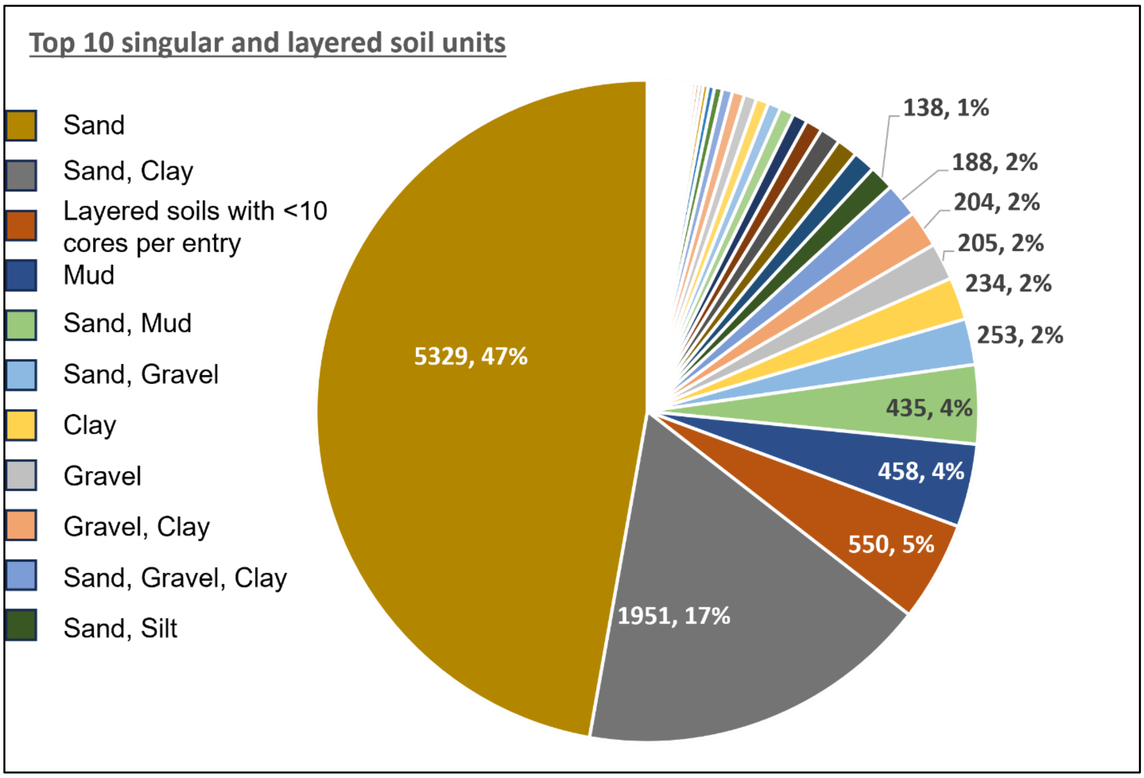


Figure 5 Pie chart showing the top ten singular and layered soil units for all cores in the North Sea study area.

3.2 ≥0.3 M BELOW SEAFLOOR

The second suite of results comprise all data with penetration depths greater than, or equal to, 0.3 m depth below seafloor. This dataset consists of 6,170 cores. The depth requirements for this dataset excludes 5,125 cores. **Figure 6** shows a pie chart displaying the distribution of the number of proven soil units within this dataset. The results from this dataset show 47.7% (2,946) of cores comprise only one proven soil unit (i.e., have just one layer). The next most common number of layered soils was two proven soil units (40%, or 2,466 of cores). The total number of cores with three layers is 592 (9.6% of the dataset), and four layers is 117 cores (1.9% of the dataset). The total number of cores with greater than or equal to five layers of proven soil units is 49 (<1%).

Figure 7 shows the breakdown of the top ten singular and layered soil units ≥0.3 m depth below seafloor. Also included in this figure are the total number of layered and unlayered soils with less than 10 cores per entry, which comes to 273 cores (4.4% of the total dataset). The dominant soil type remains sand, with 38% of the total cores in this dataset (2,346 cores), this is 9.2% less than the dataset with all cores (Section 3.1). Additionally, compared to the full dataset presented in Section 3.1, following the removal of low penetration cores, layered soil units now marginally dominate the dataset with 52.3% of the cores showing two or more layers. This is a fairly large change from 43.1% of the cores encountering two or more layers in the full dataset (Section 3.1).

The second most common soil type encountered in this dataset is SAND over CLAY (22.2%, or 1,370 cores), followed by SAND over MUD (6.4%, or 392 cores). SAND over SILT is the 9th most common soil layering type with 1.8% of the total cores (109 cores). As previously stated, (Section 2.1), mud was logged as the silt AND clay proportion of a sample (undivided), and as such a differentiation between the two soil types cannot be made.

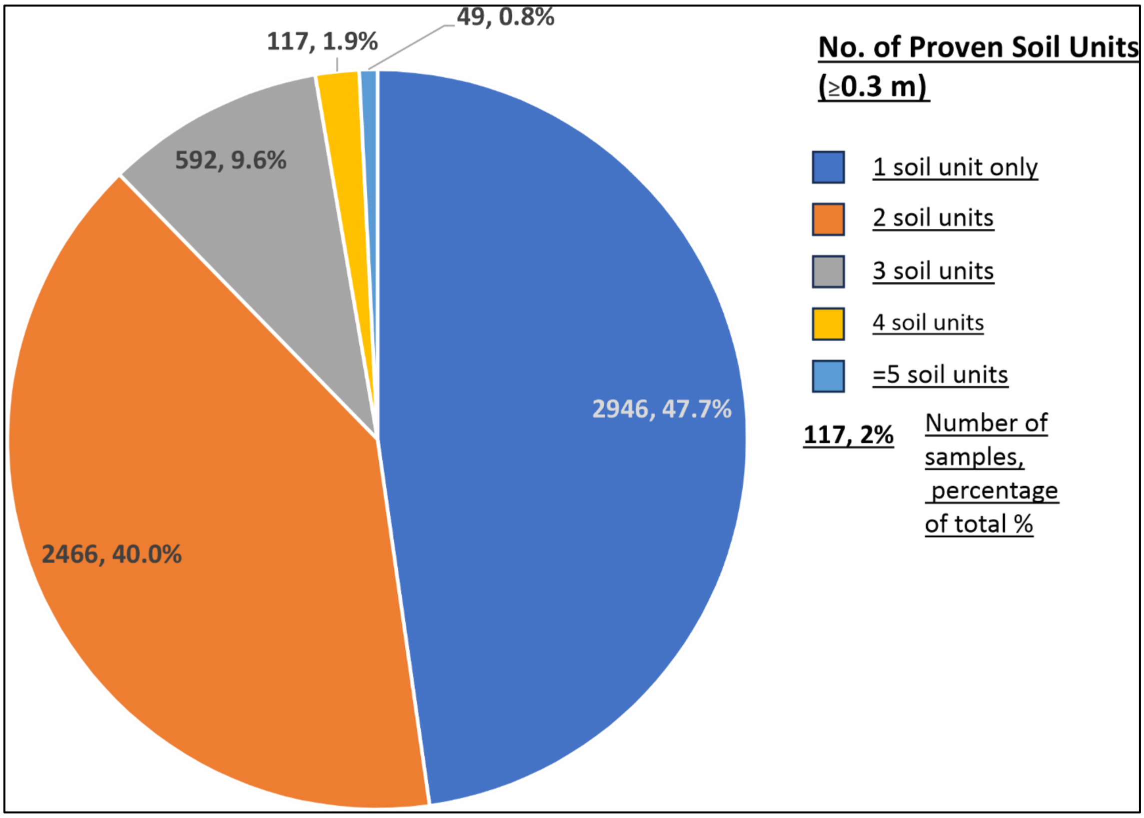


Figure 6 Pie chart showing the number of proven soil units (1 to ≥5 soil units) in cores with ≥0.3 m recovery.

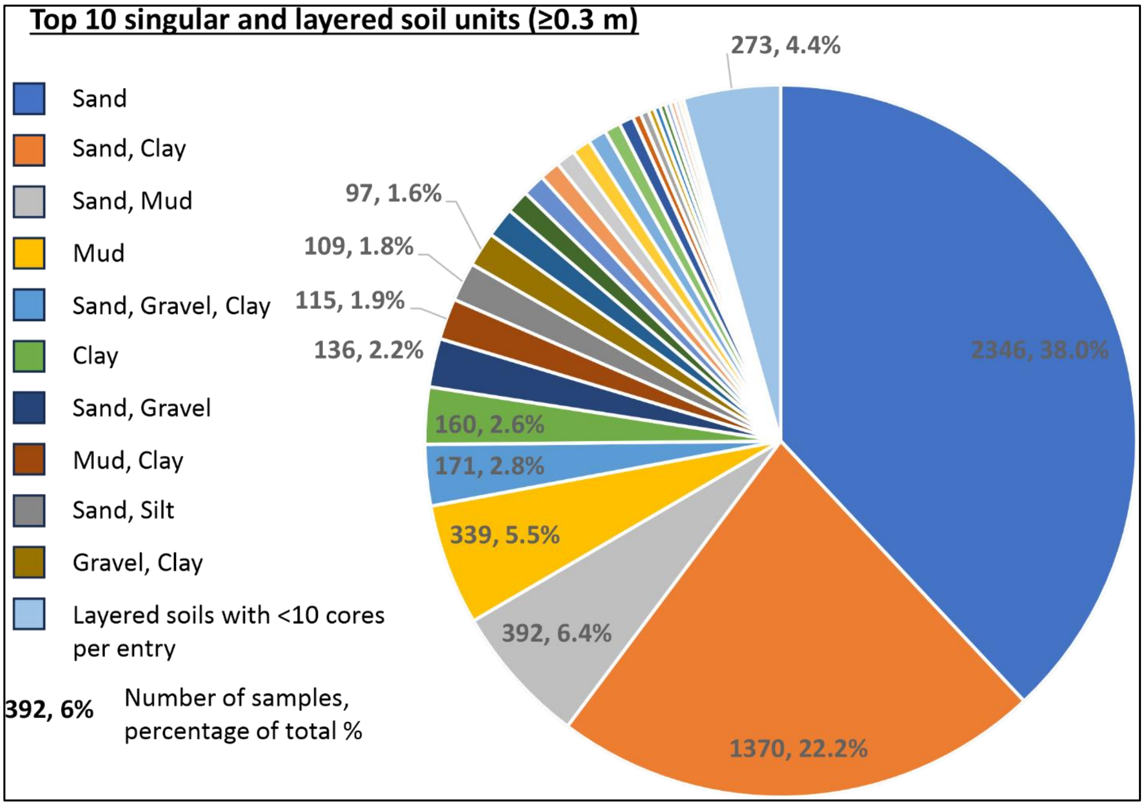


Figure 7 Pie chart showing the top ten singular and layered soil units in cores with ≥0.3 m recovery in the North Sea study area.

3.3 ≥5.0 M BELOW SEAFLOOR

This section outlines the results from a dataset of cores focussing on cores where penetration depths has been greater than or equal to 5.0 m below seafloor. As mentioned previously in Section 2.0, the current CBRA guidelines state that the depth of route-specific geotechnical data to be a nominal 5.0 m depth. The dataset presented in this subsection highlights variability of soil layers at depths extending below this nominal 5.0 m depth below seafloor.

This dataset consists of 467 cores. The depth requirements for this dataset excludes 10,828 cores. The results from this dataset show that the most common number of soil layers is two proven soil units (46.3%, 216 cores) (**Figure 8**). The second most common number of soil layers encountered is one single unit only (31.7%, 148 cores). The total number of cores with three layers is 70 (15.0% of the dataset), and four layers if 22 cores (4.7% of the dataset). The total number of cores with greater than or equal to five layers of proven soil units is 11 (2.3%).

Crucially for the aims of WP1, these results suggest that layered soils are likely to be encountered in over two thirds (68.3%) of samples taken along a potential cable corridor, should the CBRA recommended nominal depth of ~5.0 mbsf be achieved using the appropriate sampling equipment.

Figure 9 shows the breakdown of the most common singular and layered soil units from cores penetrating deeper than, or equal to 5.0 m depth below seafloor. Any layered soils with <5 cores per entry have been grouped together and account for 18.4% of the dataset (86 cores). The total number of singular soil units is 148 cores (~32% of the dataset), while the total number of layered soil units (2 – 6 layers) is 319 cores (~68% of the dataset). The dominant proven soil layering type is SAND over CLAY, at 26.8% of the dataset (125 cores). The second most common proven soil layering is SAND, with 17.8% of the dataset (83 cores). The third most common proven soil layering is also a singular soil unit – MUD, with 11.3% of the dataset (53 cores).

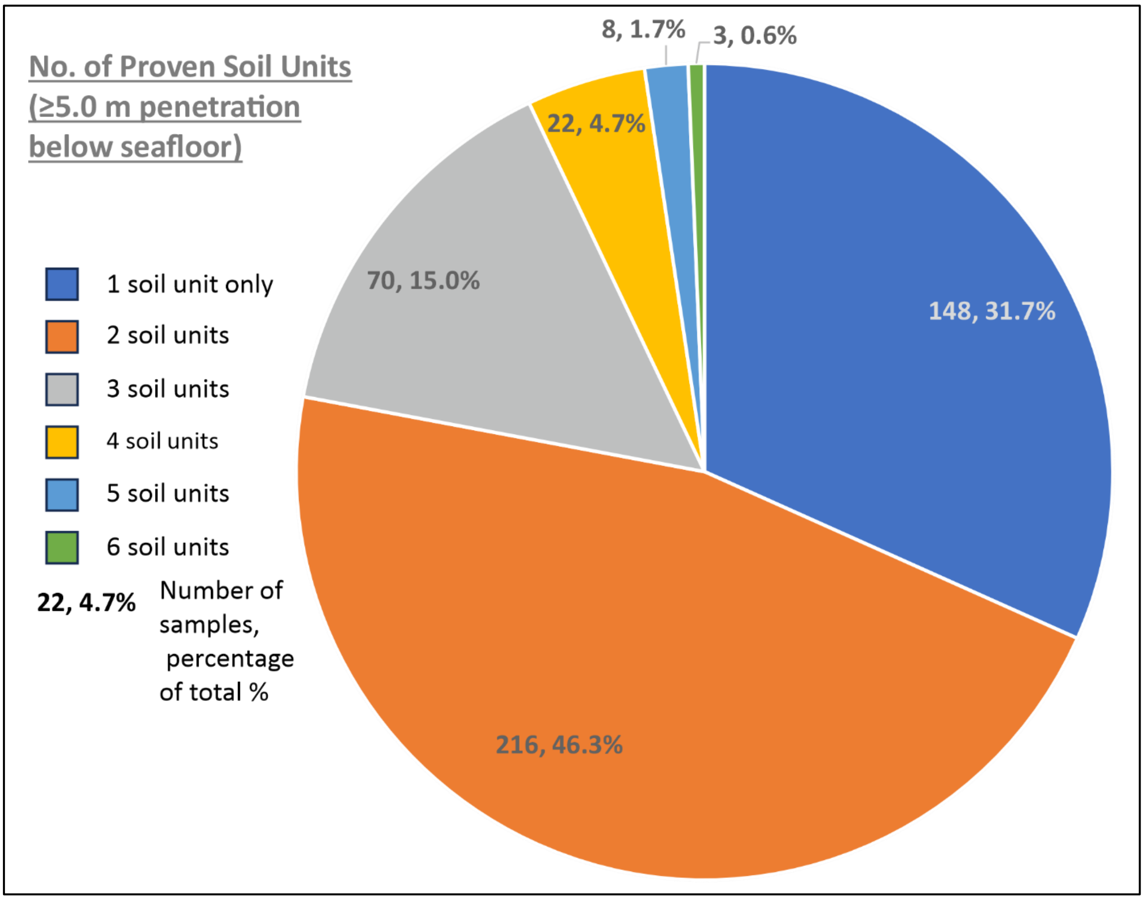


Figure 8 Pie chart showing the number of proven soil units (1 to ≥5 in all cores).

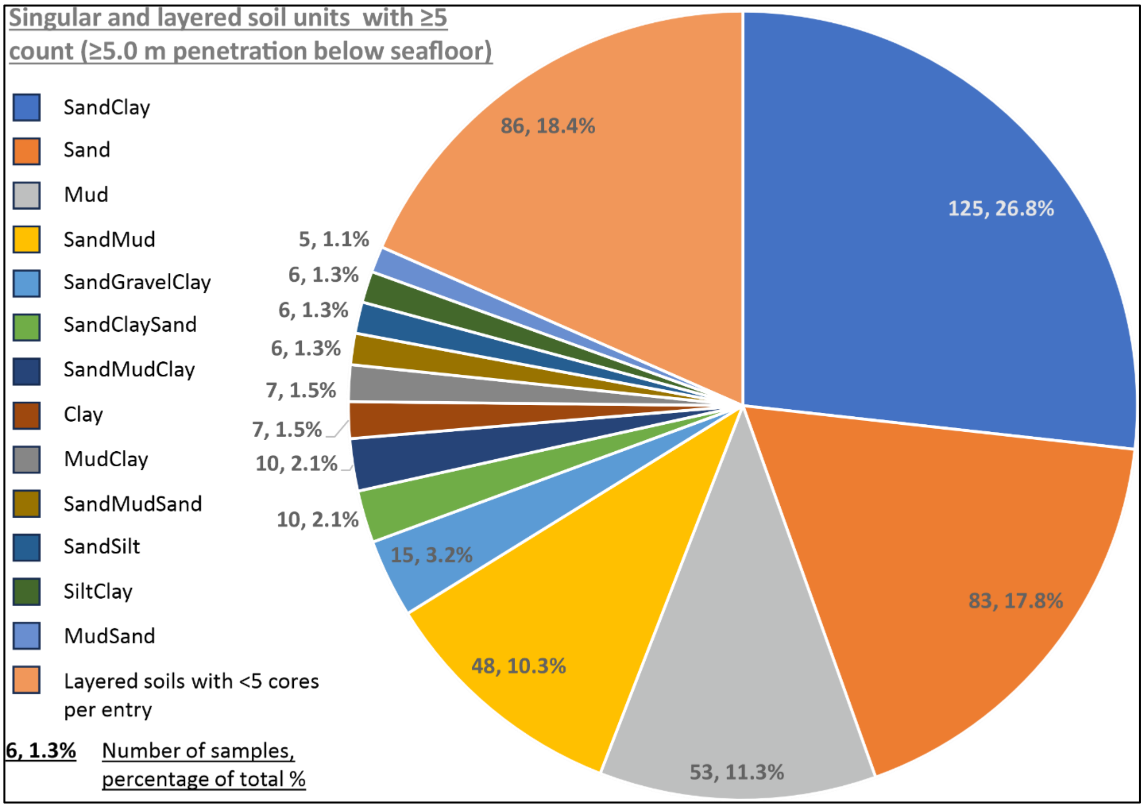


Figure 9 Pie chart showing the top ten singular and layered soil units for all cores in the North Sea study area.

3.4 PROBLEMATIC SOILS FOR TRENCHING OPERATIONS

Fibrous soils (e.g., peat) and gravel layers both present a considerable challenge to cable routing, as both can be difficult to trench through (e.g., plough deviation). Peat also causes increased soil thermal resistivity, which can lead to 'hot spots' developing and negatively impacting the cable, requiring further Operation & Maintenance (O&M) costs during the asset's lifespan. The following section outlines the results of fibrous soils (Section 3.4.1) and gravel layers (Section 3.4.2) encountered during this study.

3.4.1 Fibrous Soils

Previous work undertaken by Brown *et al*. (2015) shows that buried fibrous material, including roots and branches, can effectively reinforce granular soils (e.g., sands) and restrict the effectiveness of cable trenching works by both increasing tow force and leading to potential "ride-out" of the plough and associated significant loss of trenching depth. Fine-grained organic-rich soils are also known to restrict the dissipation of heat around HVDC export cables, which can lead to cable 'hot spots' developing, and cable maintenance being required (Hughes *et al*., 2015).

Cores that encounter fibrous soils (peat) account for just 52 cores out of the full dataset. The base depths of these peat layers varies from 0.1 m below seafloor to 6.15 m below seafloor. The peat layers encountered within the cores in this dataset are predominantly restricted to the southern North Sea (**Figure 10**). Thicknesses of the peat layers encountered vary from 0.02 m to 1.0 m (**Figure 11**).

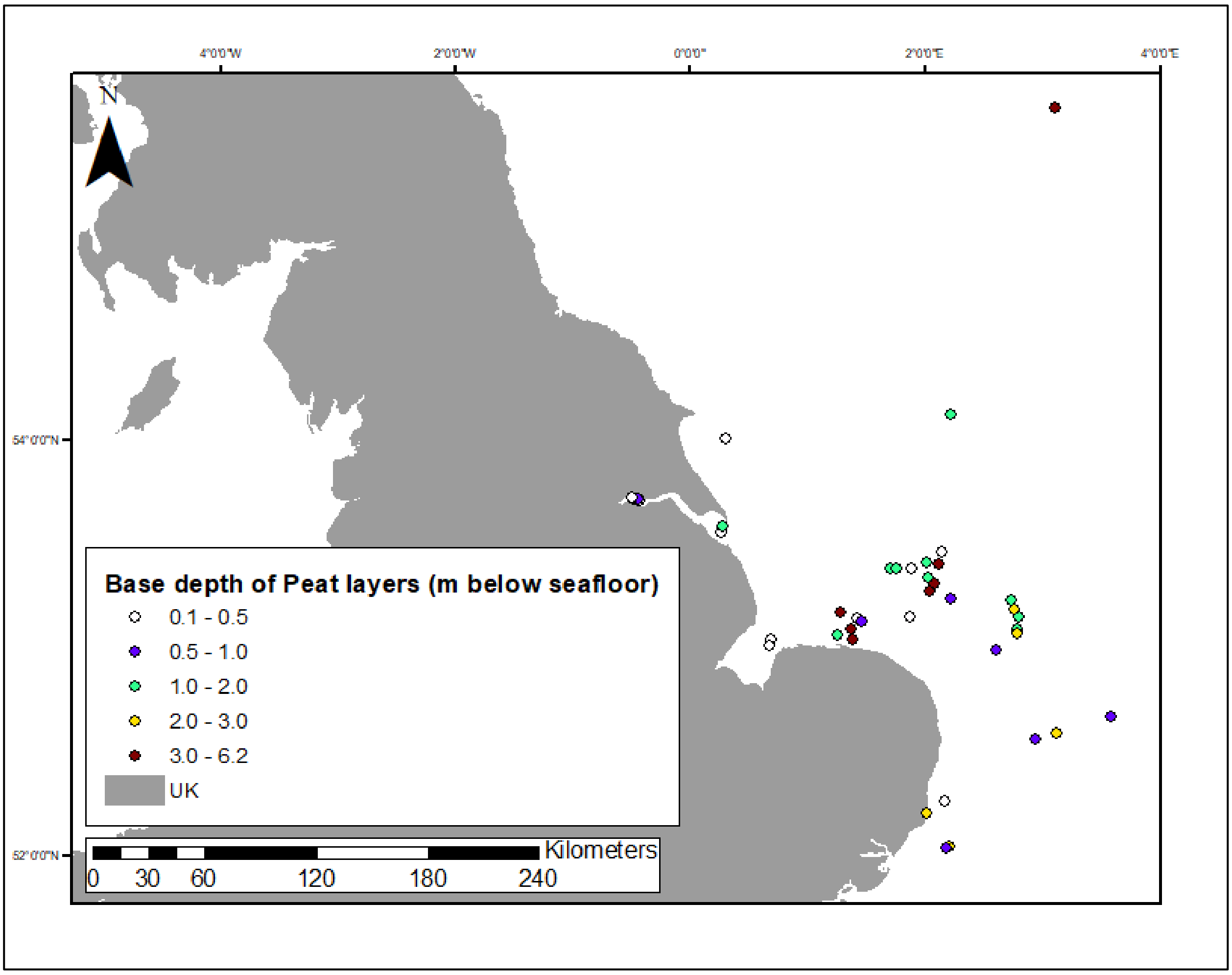


Figure 10 Map displaying generalised base depths of peat layers encountered in the core database (i.e., depth below seabed (in metres) of the base of the peat layer). Contains OS data © Crown copyright and database rights 2024.

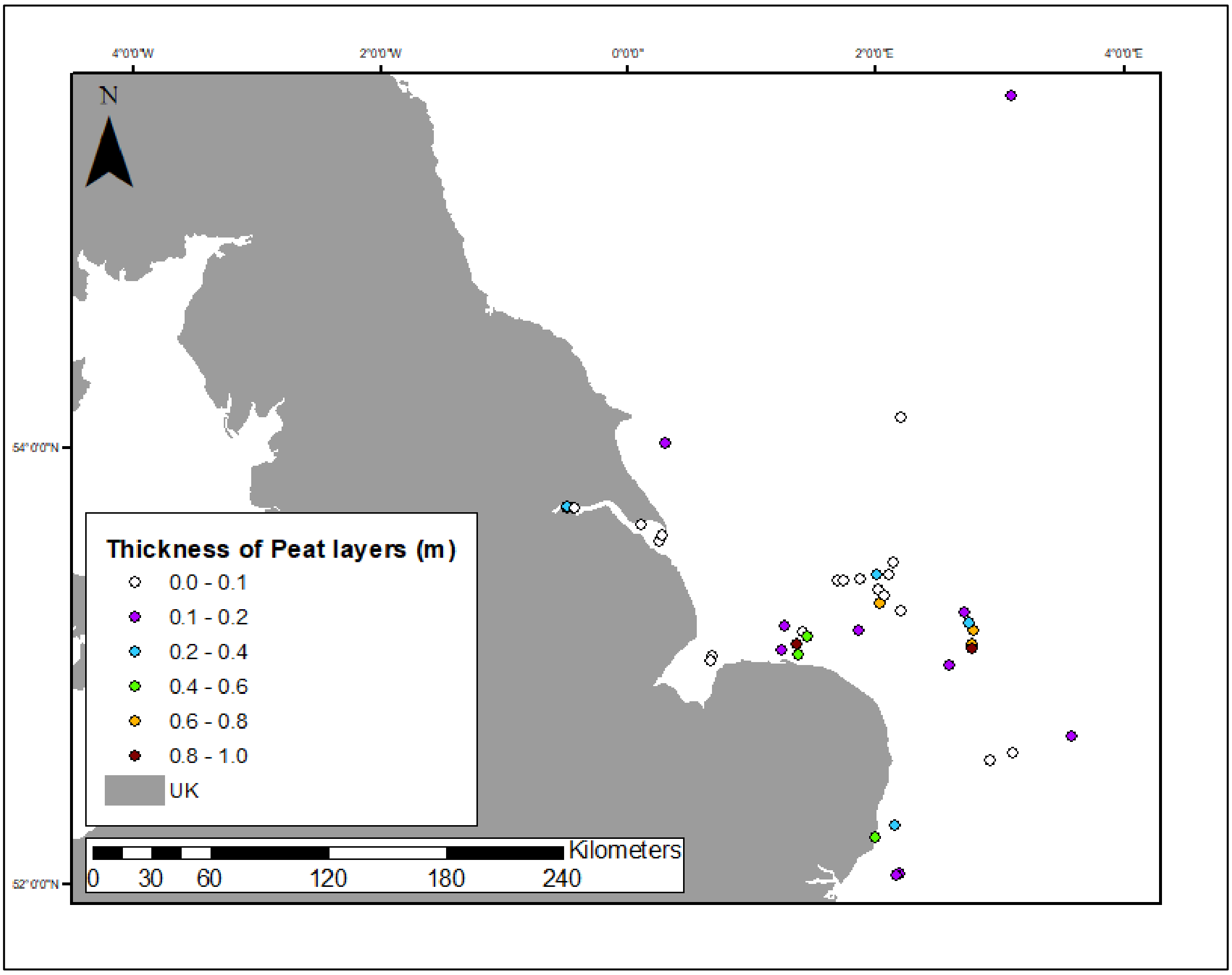


Figure 11 Map displaying generalised thicknesses of peat layers encountered in the core database. Contains OS data © Crown copyright and database rights 2024.

Figures 10 and **11** show a significant increase in instances where the word "peat" is recorded in soil logs when passing south from the Northern and Central North Sea into the Southern North Sea, with a notable cluster northeast of East Anglia. Although these are preliminary observations and further investigation is required, given the proposed extents of the Last Glacial Maximum (LGM) (see Figure 1 in Roberts *et al*., 2018 for instance) it is possible that the increase in shallow peat deposits is associated with the proglacial to post-glacial terrestrial depositional environments that would have dominated the areas south of the LGM margin.

Figure 12 displays a breakdown of the percentage of total cores encountering peat layers (52 cores in total) with regards as to the total number of layers each core encountered. Only one core that encountered peat was a single layer, while the highest proportion of soil layers in cores encountering peat was three proven soil units, with 22 cores (42.3% of the dataset). The second most common number of proven soil units is two and four, both with 25% of the dataset population (13 cores each).

Figure 13 shows that the most common layering type in this dataset is SAND over PEAT, with 11 cores (21.2% of the total dataset). Following this is SAND over CLAY over PEAT, and SAND over PEAT over SAND, both with 7 cores (13.5% of the dataset each).

Peat is most commonly found to be the second layer, with 28 cores (~54%), followed by cores which encounter peat as a third layer, (**Figure 14**). This is an important result for cable trenching preparation and tool selection, as it highlights that fibrous, organic soils are most often 'hidden' beneath a veneer of Holocene sand and therefore due diligence should be taken to avoid encountering unanticipated, unfavourable ground conditions when undertaking cable trenching works.

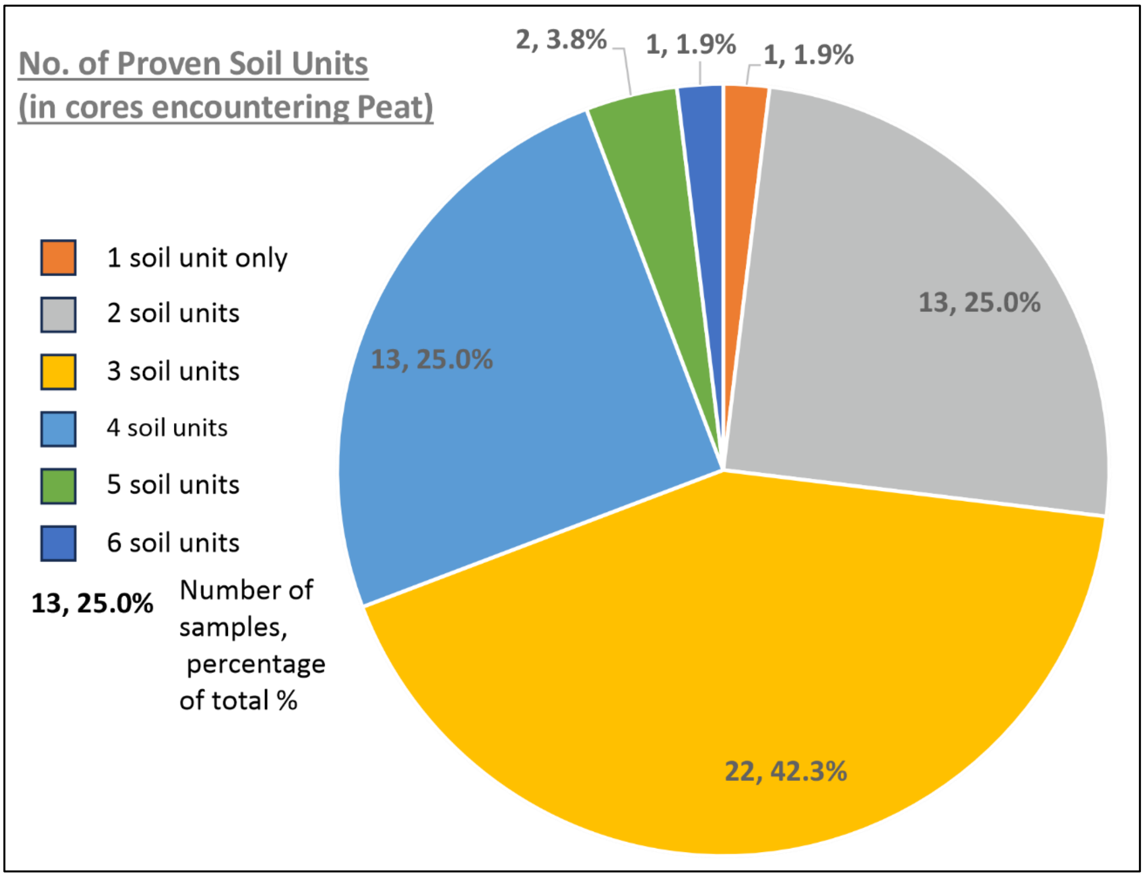


Figure 12 Number of proven soil units in cores that encounter peat. Pie chart showing the number of proven soil units (1 to ≥5 in all cores).

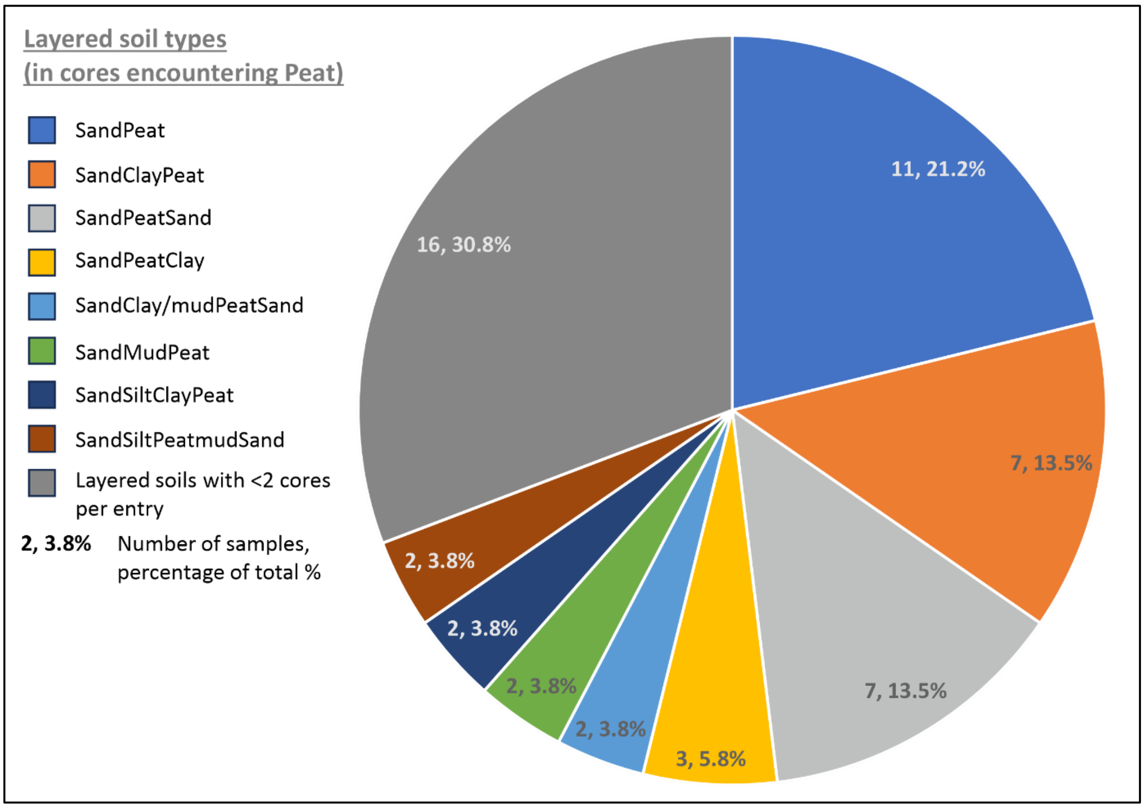


Figure 13 Most common layered soil types in cores which encounter peat. Pie chart showing the top ten singular and layered soil units for all cores in the North Sea study area.

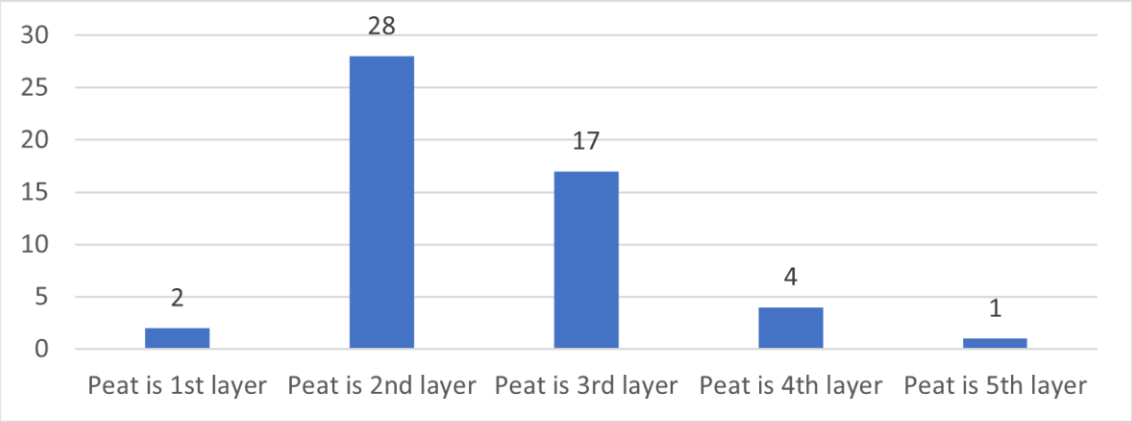


Figure 14 Order in which peat is encountered within cores that penetrate peat layers.

3.4.2 Gravel

The distribution of gravel lag deposits may have a direct influence upon cable trenching parameters employed during seabed excavation activities, as the dense nature of these deposits will provide more resistance to certain trenching methods when compared with finer muds and sands. For instance, gravels can cause deviation of seabed ploughs and are usually not suitable for jetting.

Gravel lag deposits can form in instances where the fine-grained soils have been winnowed out of seabed deposits by bottom currents, or may be a result of depositional processes, particularly resulting from high energy environments.

The occurrence of gravel specific layers within both the full dataset and the ≥0.3 m penetration depth is described in this subsection. Within the full dataset, the total number of cores encountering at least one gravel layer is 1,318 cores. Within the ≥0.3 m dataset, the total number of cores encountering at least one gravel layer is 740. In both datasets, gravel is encountered extensively across the North Sea perhaps with the exception of the mud-dominated Witch Ground Basin.

Figure 15 shows the spatial extent of cores encountering gravel layers, with the colour coding being indicative of gravel unit thickness. Although gravel deposits are present across much of the study area, they are particularly prevalent across higher-energy shallow nearshore settings as well as in locations where clast-rich glacial diamict (i.e., till) are present at or near seabed (e.g., Bolders Bank Formation). This suggests that winnowing of the fine-grained soil matrix forming the diamict may have contributed to the accumulation of coarser-grained gravel deposits in many instances.

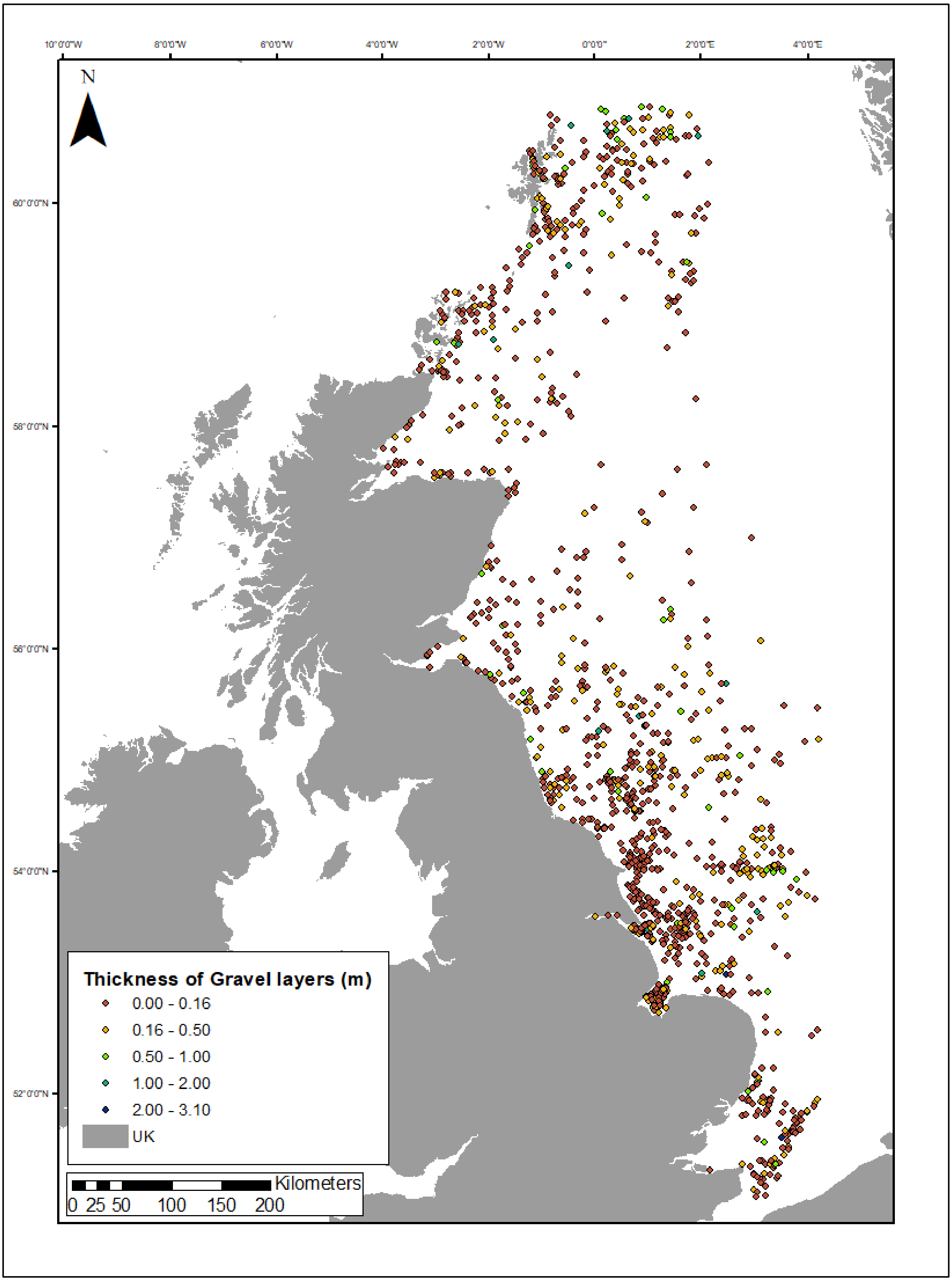


Figure 15 Map of cores encountering gravel units colour coded with the thickness of the units encountered (meters). Gravel layers can be seen throughout the North Sea. Contains OS data © Crown copyright and database rights 2024.

3.4.2.1 FULL DATASET WITH GRAVEL LAYERS

Within this subset, the total number of cores encountering at least one gravel layer is 1318. These gravel layers are encountered anywhere between 0.0 (at seafloor) and 5.62 m depth below seafloor. Thicknesses of the gravel layers within this subset ranges from 0.02 to 3.09 m.

Figure 16 displays a breakdown of the percentage of total cores encountering gravel layers across the full dataset. A total of 205 cores feature gravel as the only soil unit (15.6% of the total dataset), although caution should be taken when evaluating these results as dense gravels at seabed are highly likely to cause premature refusal of coring equipment resulting in just a single soil unit being recovered when in reality there are other soil units of different composition beneath the seabed gravel layer and within cable burial depths. The most common number of proven units including gravel layers is two units, with 637 cores (48.3% of the full dataset). The second most common number of proven units including gravel layers in three units, with 384 cores (29.1% of the full dataset). **Figure 17** displays a breakdown of the 10 most common layering types encountered in this dataset. The most common layering type in this dataset is SAND over GRAVEL, with 255 cores (19.3% of the total dataset). Following this the singular GRAVEL layer is the second most common layering type encountered, with 205 cores (15.6% of the total dataset). The third most common layering type is GRAVEL over CLAY, with 204 cores (15.5% of the total dataset).

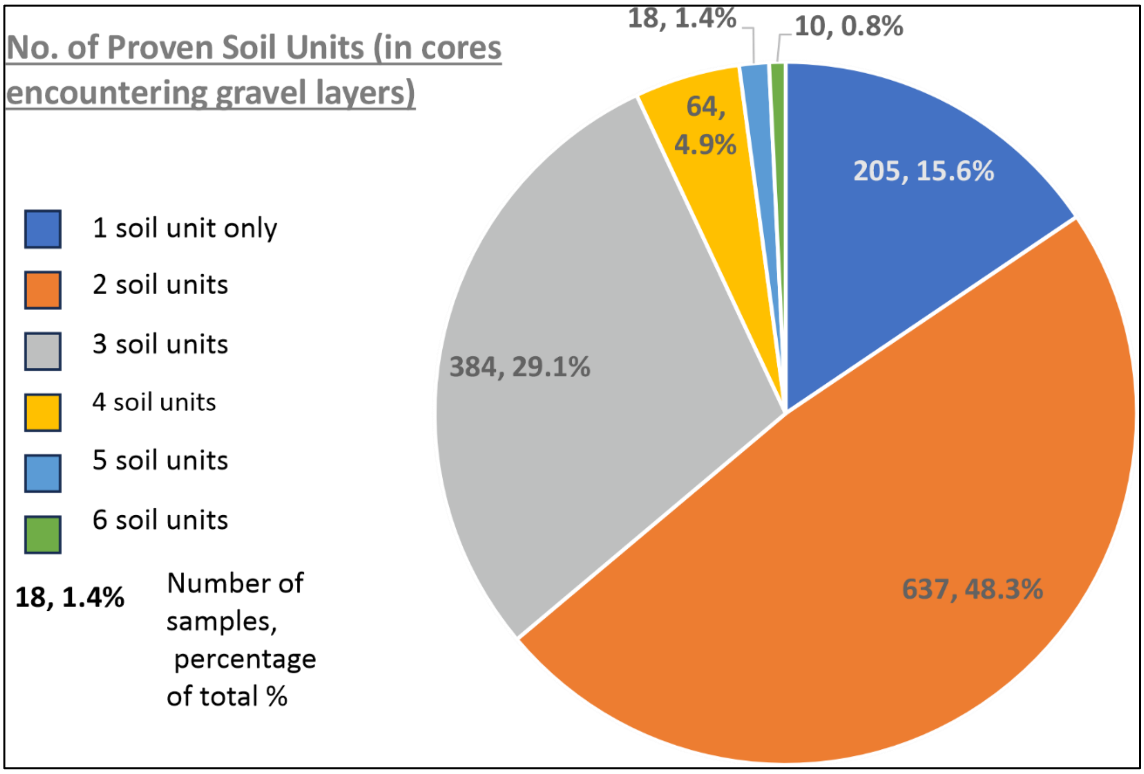


Figure 16 Number of proven soil units in cores that encounter gravel. Pie chart showing the number of proven soil units (1 to ≥5 in all cores).

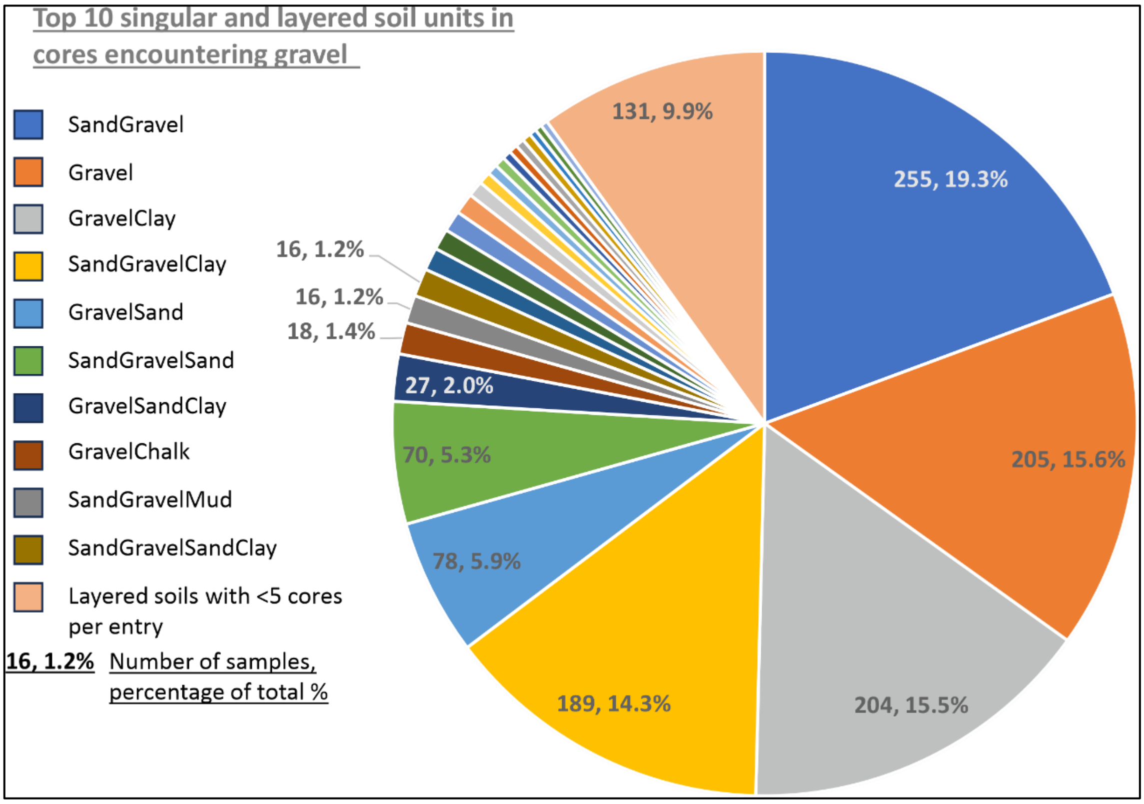


Figure 17 Most common layered soil types in cores which encounter gravel. Pie chart showing the top ten singular and layered soil units for all cores in the North Sea study area.

3.4.2.2 ≥0.3 m Dataset with Gravel layers

Within this subset, the total number of cores encountering at least one gravel layer is 740. These gravel layers are encountered anywhere between 0.3 and 5.62 m depth below seafloor. Thicknesses of the gravel layers within this subset also ranges from 0.02 to 3.09 m.

Figure 18 displays a breakdown of the percentage of total cores encountering gravel layers across the ≥0.3 m dataset. A total of 35 cores feature gravel as the only soil unit (only 4.7% of the subset, a significant reduction when compared with gravel-only layers in the full dataset). The second most common number of proven units including gravel layers is two units, with 272 cores (36.8% of the subset). The most common number of proven soil units that includes a gravel layer is three units, with 345 cores (46.6% of the subset).

Figure 19 displays a breakdown of the 10 most common layering types encountered in this dataset. The most common layering type in this dataset is SAND over GRAVEL over CLAY, with 170 cores (23% of the subset of data). Given the Quaternary history of the shallow soil units across the North Sea (i.e., a previously glaciated margin), some of these gravel units are likely to be derived from the underlying clay-rich glacial diamict (till) through winnowing out of fine-grained soils (clay matrix), and subsequently covered with a veneer of Holocene surface sands. Following this, SAND over GRAVEL is the second most common layering type encountered, with 106 cores (14.3% of the subset). The third most common type of soil layering within this subset is GRAVEL over CLAY, with 93 cores (12.6% of the dataset) which again may be related to winnowing of clay particles out of glacial diamict (till), leaving a gravel-rich lag across the seabed.

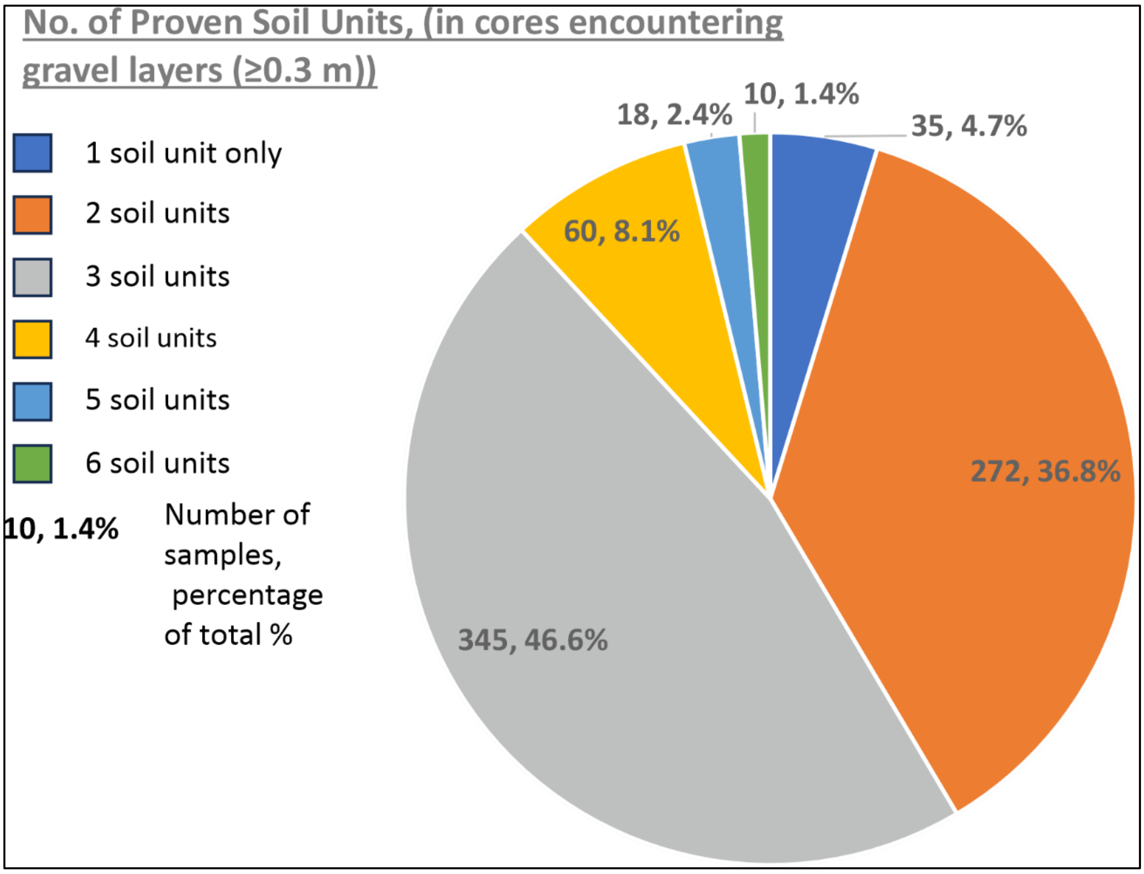


Figure 18 Number of proven soil units in cores that encounter gravel in cores penetrating deeper than, or equal to 0.3 m below seafloor.

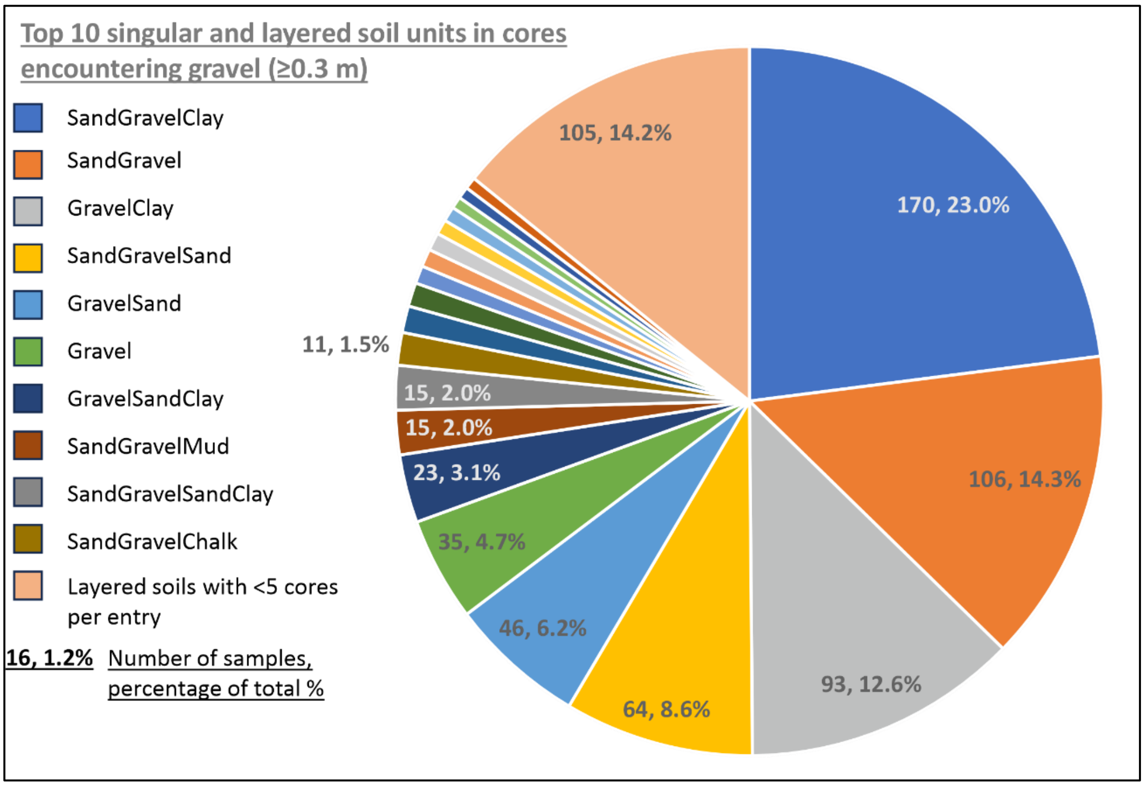


Figure 19 Most common layered soil types in cores which encounter gravel in cores penetrating deeper than, or equal to 0.3 m below seafloor. Pie chart showing the top ten singular and layered soil units for all cores in the North Sea study area.

3.5 VARIABLE QUATERNARY SOIL UNITS OF THE NORTH SEA

Figure 20 demonstrates the lateral and vertical variability of ground conditions encountered within this study area within cable burial depths (<6 m below seafloor). This figure shows an idealised cross-section along a hypothetical subsea cable route. Core profiles (including geotechnical properties) used in this figure are all real-life examples located within the southern North Sea. It must also be stated that the target DoL is typically shallower than 6 m below seafloor, however this depth was chosen due to the requirement from the Carbon Trust (2015) guidelines stating that route-specific geotechnical data should be to a depth of at least 5 m below seafloor. Soil profiles and associated undrained shear strength (s_u) plots within **Figure 20** are all taken from real-world examples from the unitisation database compiled for this study, with undrained shear strength chosen for this example as previous analysis (Jones, 2018) suggests that anchor penetration depths are sensitive to undrained shear strength of the soil unit in clays in particular.

Core 54+2/183/VE/1 encounters "fine to medium grained SAND with abundant shell fragments" to a depth of 0.88 m, "brown coarse grained sandy GRAVEL with abundant shell fragments and occasional cobbles" from 0.88 m to 1.06 m and a "very stiff reddish brown silty sandy CLAY" from 1.06 m to the base of the core at 3.51 m. The sand encountered at the top of the core is likely Holocene marine sand cover. The gravel unit most likely represents a gravel lag, generated through winnowing out of a finer grained matrix (clay to sand fraction) of a lower unit. This type of deposit is common throughout the North Sea, as well as the North Atlantic Margin (Carr, 1999; Diesing *et al*., 2009; Howe *et al*., 2001). The final unit encountered, the very stiff CLAY shows a very high strength and relatively uniform undrained shear strength profile of 172 kPa to 197 kPa. This unit most likely represents a glacial diamicton (commonly known as a till or boulder clay), and similar examples of glacial diamicton with comparable s_u profiles have been identified across the North Sea at or near the seabed (<5.0 m below seafloor) (Roberts *et al*., 2018).

Core 54+1/120/VE/1 encounters "well sorted fine SAND with ~5% lithic fragments and shell fragments" to a depth of 0.30 m and a "grey homogenous CLAY with rare clasts of chalk" from 0.30 m to the base of the core at 3.80 m. The sand encountered at the top of the core is likely representative of Holocene marine sand cover and the clay unit below likely represents a glacial diamicton. The s_u profile of the clay unit of this core is vastly different to that of core 54+2/183/VE/1, in that it is much more varied, ranging from medium (75 kPa) to very high (180 kPa) strengths within just the upper section of the clay unit sampled. This example demonstrates the extremely variable nature of soil strengths that can be found particularly within glacially deformed soils such as moraine complexes. This variability can be caused by thrusting, folding and incorporation of soil units deposited in varied environments into said moraine complexes, and can lead to unexpected strength readings, even in just a small section of a unit sampled.

Core 54+2/152/VE/1 encounters "gravelly SAND with pebbles to 8 cm and little shell debris" to 0.25 m depth and a "reddish dark brown stiff to hard 180 kPa silty sandy CLAY with chalk granules common up to 4 cm in size" from 0.25 m to the base of the core at 3.61 m. The gravelly sand encountered is most likely a combination of Holocene marine sands and winnowed coarser material from the clay below. The clay encountered is most likely a glacial diamicton. This core is similar to 54+2/183/VE/1, both in soils encountered and the s_u profile of the clay unit sampled.

The last core in the schematic (**Figure 20**) is core 54+2/121/VE/1. This core encounters "dark grey slightly olive very well sorted SILT" to a depth of 0.75 m and a "silty CLAY with frequent fine sand laminae and occasional evidence of bioturbation" from 0.75 m to the base of the core at 5.20 m below seafloor. The uppermost sand unit encountered in the other three cores is here replaced by silt, while the lower clay unit exhibits extremely low (5 kPa) to very low (14 kPa) undrained shear strengths. This clay unit was most likely deposited under glaciomarine conditions, with marine gastropods *turritella* identified through the unit.

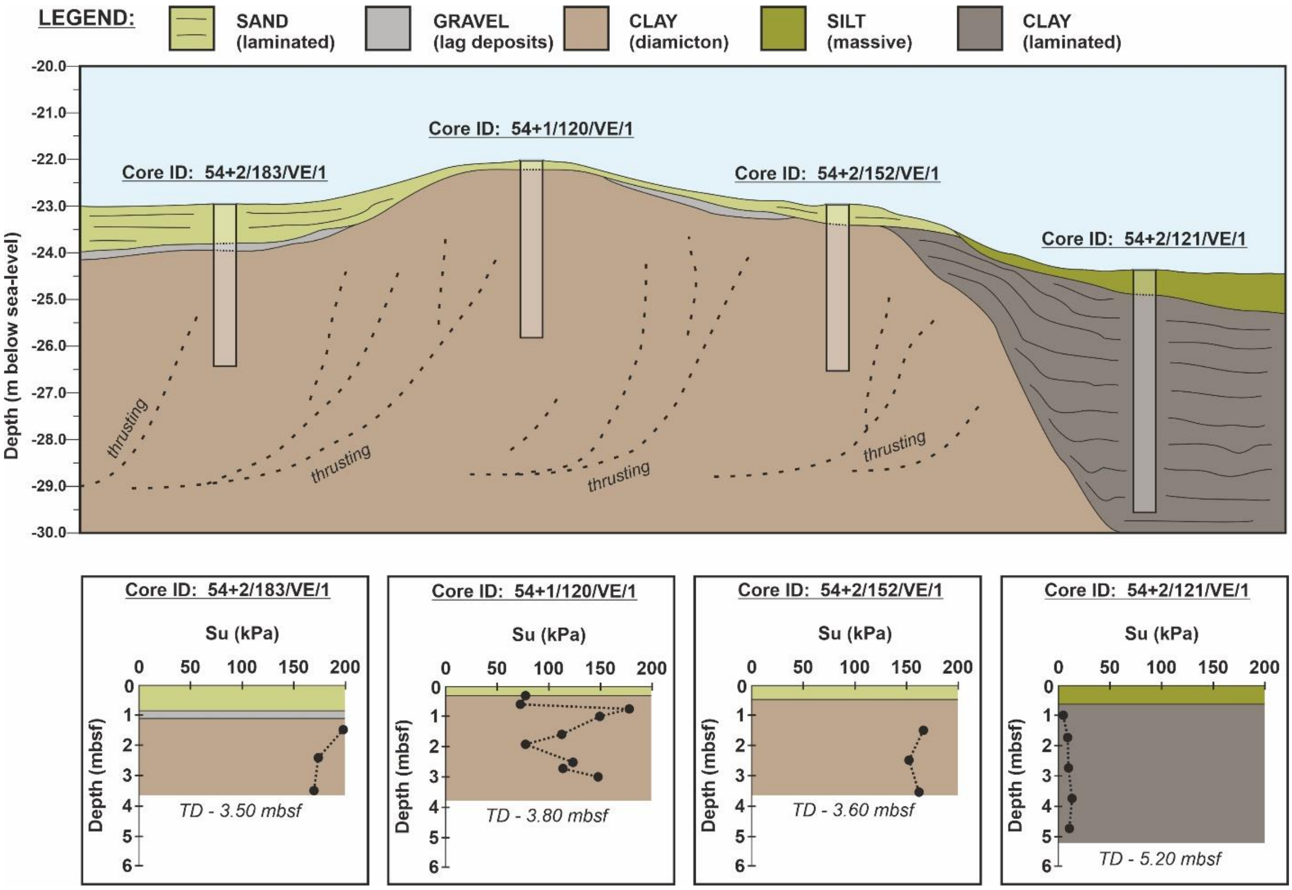


Figure 20 Conceptual cross-section along a hypothetical offshore cable route in the North Sea including example soil profiles and associated undrained shear strength plots (s_u) which have been extracted from the BGS offshore core database.

3.5.1 Variable clay and (undivided) mud strength across the North Sea

The distribution of recorded clay and mud strength is shown in **Figure 21**. This figure uses strength measurements that explicitly record very soft, soft, firm, stiff and very stiff measurements (a total of 2904 recorded measurements, out of 3569 recorded measurements). There are additional strength measurements within the database, but these typically record ranges (i.e., soft to firm) or measurements such as “tough”, “buttery” or “compact” and are not regarded as current standardised field test measurements of strength (**Table 2**). It must be noted that it cannot be guaranteed that these were the field tests used to record strength in the geological logs presented in the unitisation spreadsheet and this report.

BS 5930:2015						
Term	Very soft	Soft	Firm	Stiff	Very stiff	
Field test	Finger easily pushed in up to 25 mm. Exudes between fingers	Finger pushed in up to 10 mm. Moulded by light finger pressure	Thumb makes impression easily. Cannot be moulded by fingers. Rolls to thread	Can be indented slightly by thumb. Crumbles in rolling thread. Remoulds	Can be indented by thumb nail. Cannot be moulded, crumbles	

BS 5930:1999						
Term	Very soft	Soft	Firm	Stiff	Very stiff	Hard (or extremely weak)
Field test	Finger easily pushed in up to 25 mm; exudes between fingers	Finger pushed in up to 10 mm; moulded by light finger pressure	Thumb makes impression easily; cannot be moulded by fingers; rolls to thread	Can be indented slightly by thumb; crumbles in rolling thread; remoulds	Can be indented by thumb nail; cannot be moulded, crumbles	Can be scratched by thumb nail
BS 5930:1981						
Term	Very soft	Soft	Firm	Stiff	Very stiff	
	Exudes between fingers when squeezed in hand	Moulded by light finger pressure	Can be moulded by strong finger pressure	Cannot be moulded by fingers. Can be indented by thumb	Can be indented by thumb nail	

Table 2 Standardised field tests for soil strength from BS 5930:2015, BS5930:1999 and VS5930:1981.

Figure 21 illustrates strength variability at each data point (e.g., sediment core location). This plot is based upon the qualitative description for each clay unit encountered within cable burial depths (e.g., very soft to extremely stiff). An example is given in Section 5.2 of further work that can be undertaken as part of Work Package 6 to develop quantitative shear strength (S_u) maps for data-rich areas of the North Sea, using an average (mean) shear strength value (in kPa) for depth ranges (e.g., 0.0 – 0.5 mbsf) within the CBRA zone of interest. Geospatial product of this nature may be beneficial to the subsea cable burial industry as baseline datasets to guide anticipated ground conditions but would not aim to replace a route-specific assessment.

shows a broadly north-south divide where very soft to soft clays and silts (or undivided 'muds') are far more prevalent within the northern North Sea. These are often associated with muddy estuarine settings (e.g., the Forth Estuary) and also deeper-water basins such as the Witch Ground Basin offshore of NE Scotland. These settings provide sinks for fine-grained particles accumulating in late-glacial to Holocene marine environments.

Conversely, firm to very stiff clays and muds are more commonly found across the southern North Sea. A pattern of stiff to extremely stiff clays is apparent offshore of the Humber Estuary area to the Norfolk Coastal area and out into the southern North Sea. This is in line with previously mapped ice limits of the Weichselian aged (Marine Isotope Stage 5-3) North Sea lobe of the British and Irish Ice Sheet based on seabed morphology (see Figure 10 in Dove *et al*., 2017). Additional ice limits have been mapped using a combination of seabed morphology, sub-seabed geophysical profiles and some of the cores used in this study and correlate well with the extent of the stiff to extremely stiff cores offshore Norfolk and Lincolnshire (**Figure 21**).

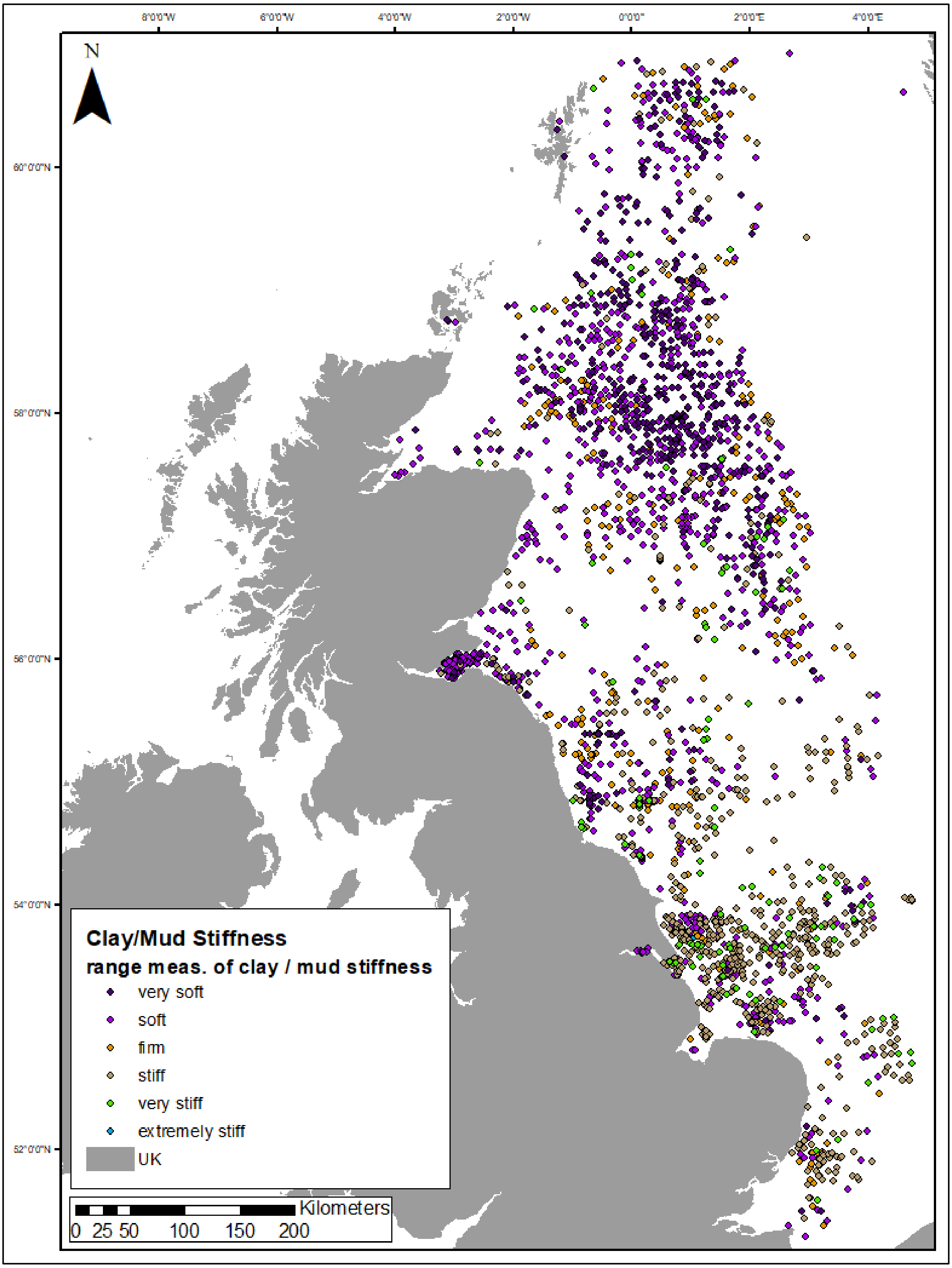


Figure 21 Map of clay and mud strength distribution from unitisation database. Contains OS data © Crown copyright and database rights 2024.

4 Discussion

As shown in **Figures 4** and **6**, single-unit soil profiles make up a significant proportion of the cores used in this study across the North Sea. These results (**Figure 4** in particular) are likely to be fairly conservative, due to the "penetration problem" previously mentioned (Section 3.1). Within this study, 5122 cores were found to penetrate less than 0.3 m below seafloor, and with the removal of these cores, samples with only a single layer encountered was reduced by 16.2% (from 56.9% of the full dataset, to 47.7% of the ≥0.3 m dataset). **Figure 22** presents a schematic representation of the effect of differential penetration observed in the current database presented in this report. For example, despite three to four soil layers being present within <5 mbsf in this diagram, where there is recovery of ~0.3 m, only one layer is sampled. Where there is recovery of around 3.0 m, two layers are encountered, the same sand as before and sandy silt below. Where recovery is around 5.0 m below seafloor, four layers are encountered, the previous sand and silt, a thin gravel lag and finally a clay dominated glacial till. To further illustrate this problem, we include in this report a further limited dataset where only cores penetrating 5.0 m or deeper were included (Section 3.3). Here the percentage of this subset of data encountering just one layer is reduced to 31.7% of the ≥5.0 m subset (148 cores in total). The most common number of soil layers encountered within this subset was two layers, at 46.3% of the dataset (216 cores). This is an increase from the ≥0.3 m subset (40%, or 2,466 of cores), and an even more drastic increase from the full dataset (35%, or 3,964 of the cores).

The examples described above serve to demonstrate that multilayered soil profiles are very common across the North Sea study area presented in this report, particularly concerning the Quaternary stratigraphy commonly encountered at cable burial depth and depth of lowering. In addition to this, internal physical properties of both single and multilayered soil unit combinations show alterations to physical properties, influenced by Quaternary depositional history on the shallow subsurface. These influences and alterations have the potential to significantly impact DoL assessments.

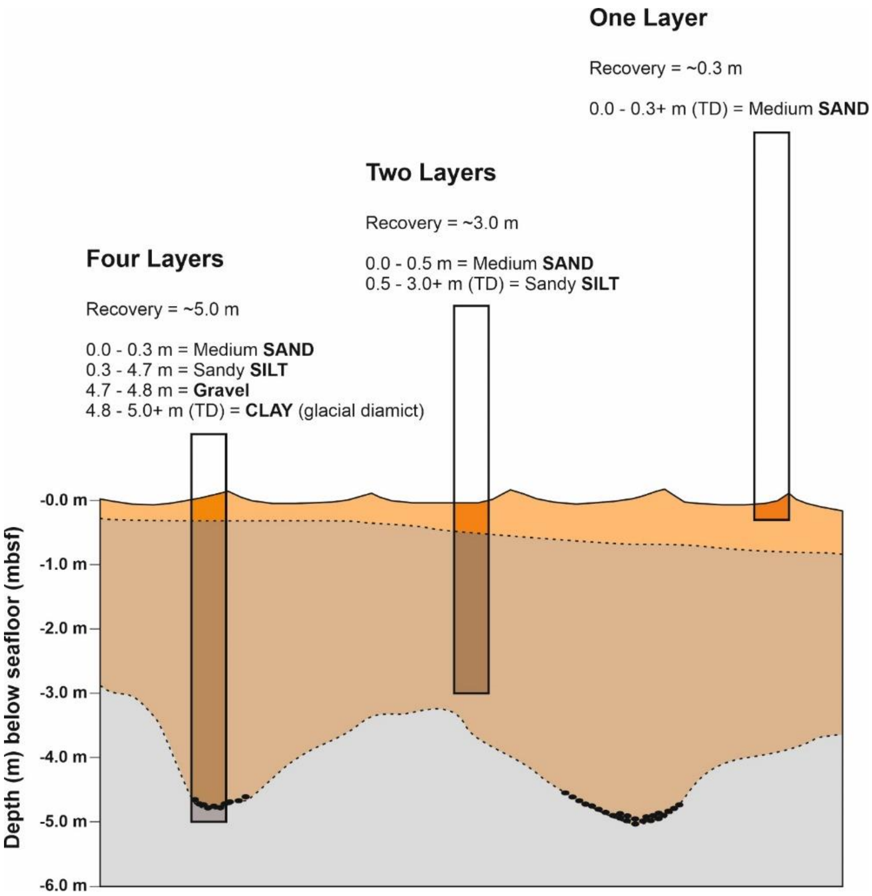


Figure 22 Schematic representation of the low penetration problem encountered within the database used in this report.

4.1 GEOTECHNICAL CONSIDERATIONS WITHIN VARIABLE QUATERNARY SOIL UNITS OF THE NORTH SEA

Through the unitisation exercise presented in this report, it is clear that soil layering within the nominal 5 m depth below seafloor is present across the North Sea. This soil layering has the potential to impact DoL significantly and is present in some cases within even the top 1 m of the subsurface. Although further work is required to assess real-world CPT profiles, in order to investigate changes in geotechnical properties associated with layered soil units, examples can easily be drawn upon from Site Investigation reports that are available in the public domain to further demonstrate the presence and complexity of layered soils (**Figure 23** illustrates three examples from different offshore wind farm sites across the North Sea study area).

Figure 20, discussed in Section 3.5, is used to highlight the importance of understanding variable strengths in single soil units, particularly in clays. The four cores and relevant s_u plots used in the diagram are all factual data included in the overall unitisation spreadsheet resulting from the work conveyed in this report. Three of the four cores used in the example contain glacial diamict beneath surficial sand (and gravel on one occasion). These three occurrences of glacial diamict are encountered within ~1 m of the seabed and all show firm to stiff (>75 kPa) clay units beneath the surficial soil layers. This combination of soil units and strengths at such a shallow depth may result in limited DoL, depending on the chosen cable burial solution. This can risk shallow burial along the cable route, resulting in asset exposure, and risks of cable-anchor interactions.

On the other hand, one of the cores used in the example (core 54+2/152/VE/1) encountered a very soft silty clay, with s_u measurements of <10 kPa within 1 m below seafloor. This softer material has the potential to allow for much deeper anchor penetrations than expected. The result of this type of soil within a cable burial area is that DoL may not be economically or technically viable as the DoL necessary to protect the asset may be too great.

A key point to take from this example is that the approach of modelling a single clay unit with a uniform strength profile does not always reflect real world data. Anchor penetration depths can be heavily impacted by variable shear strength throughout a single clay unit, as can DoL for cable burial. It is also important to note that the depositional environment, post-depositional processes, and historical stress regimes are heavily linked to the physical properties exhibited by soils, as evidenced by the difference in s_u profiles between the glacial diamicton and glaciomarine clays (core 54+2/183/VE/1 versus core 54+2/121/VE/1, respectively, **Figure 20**). These complexities are not taken into account with the current CBRA methodology, which instead relies on a singular, dominant seabed classification.

Similarly, variable relative densities (D_r) within a single sand unit can also have a significant influence over anchor penetration depths. Work conducted as part of this EPSRC project by the University of Dundee has identified the importance of sand relative density on the required DoL of seabed cables. As opposed to the guidance from the Carbon Trust document, which states 1 fluke length of penetration in sand, the centrifuge experiments conducted at the University of Dundee have indicated that in loose sand beds, significant penetration of the drag embedment anchor (DEA) can occur. As the relative density of the sand increased, the depth of anchor penetration decreased (from 2.5 fluke lengths in loose to 0.4 fluke lengths in dense), highlighting the importance of characterising both the soil type and the relative density (D_r) of granular soils.

Further to this is the necessity of understanding the past environmental and depositional history of the region. Throughout the Quaternary (2.58Ma to present day), the UK continental shelf experienced multiple glacial and interglacial periods. This is reflected in the vertical and horizontal anisotropy expressed in **Figures 20-23**. This anisotropy impacts not just the upper 5 m of the subsurface but can extend well over 100 m below seabed in deeper basins. Across the North Sea, glacial and proglacial deposits comprise a variety of different soil types, from stiff to very stiff clays (tills and glacial diamict) with abundant gravel to boulder-sized clasts ranging from chalk to granite in lithology; glacial outwash or sandur deposits comprising well sorted sands, silts and gravels; channelised and interbedded sands, silts, gravels; low energy environment (lacustrine and ponded) rhythmically laminated clays, silts and fine sands; fan and deltaic deposits comprising reworked clay, silt, sands, gravels and boulders; and glaciomarine deposits comprising very soft to soft silts and clays. Alongside this depositionally derived anisotropy, vertical and lateral variability will have also been caused by glacial and periglacial processes, such as freeze-thaw and desiccation, both of which can have an impact on the internal strength of soil units.

During interglacial and postglacial periods flooding of previously aerially exposed areas has occurred several times, and of particular importance to cable burial depths is the Holocene transgression which occurred following the last glacial maximum. The shallow subsurface shows evidence of this flooding in the deposition and preservation of organic rich estuarine and coastal deposits (such as peat) (Emery *et al*., 2019), causing challenging trenching conditions (Brown *et al*., 2015).

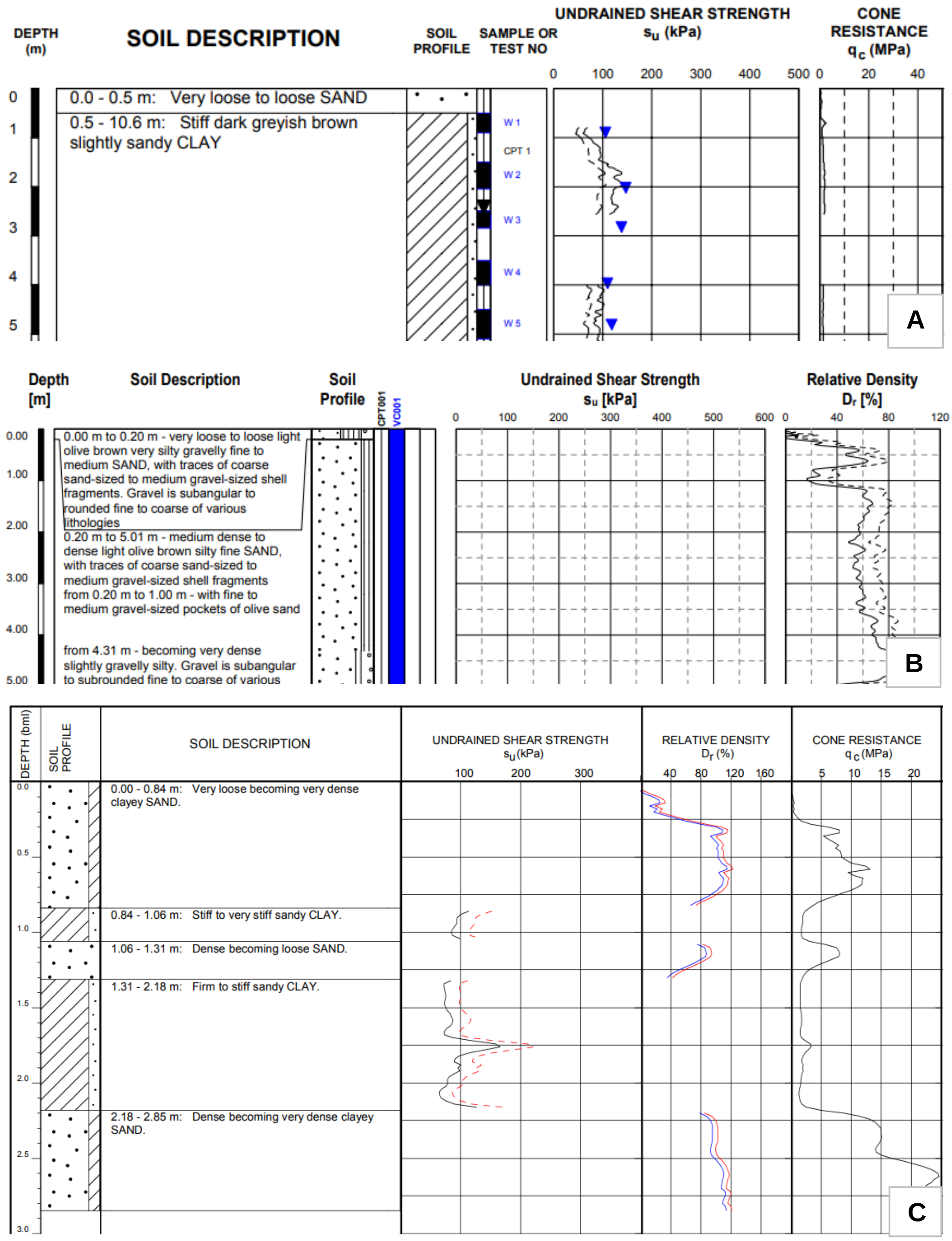


Figure 23 Examples of CPT profiles from three offshore wind farm sites across the North Sea, with each demonstrating different layered soil combinations and associated geotechnical properties (A. Dogger Bank; B. Thanet; C. Lincs). Contains data from the Marine Data Exchange portal (https://www.marinedataexchange.co.uk/) © Crown Copyright 2013.

5 Conclusions & Further Work

5.1 CONCLUSIONS

WP1 had the primary aim of contextualising the issue of layered soils within cable burial depths by using real-world data examples from the North Sea to assess:

- Whether layered soils are in fact common within the upper <6 m below seabed and, if so;
- What the most statistically significant layering combinations are, focusing on various subsets of the data as agreed in advance with an Industry Steering Group.

Key results include the following:

- When considering the full dataset (0.0 – 6.0 mbsf), single soil units (i.e., exhibiting no layering) accounted for 56.9% of the dataset, or 6,426 cores out of the 11,295 cores. Therefore, 4,869 cores (43.1%) did display some degree of layering, between 2 and >5 layers recorded in core logs. The most common single or layered soil combination recorded in logs was single (homogeneous) Sand at 47% (5,329 cores), followed by Sand over Clay at 17% (1,951 cores).
- When removing the shallow penetration (<0.3 mbsf) samples, that tended to only recover the seabed surface sediments (typically modern sands) and thus skewed results to single (non-layered) sand profiles, it was noted that single soil units now only comprised less than half (47.7%, 2,946 cores) of the overall 6,170 cores in this subset. This meant that layered soil combinations of 2 to >5 layers now accounted for a marginal majority of 52.3% of the dataset. Single (non-layered) Sand profiles still dominated with 38% (2,346 cores) of the total dataset, with Sand over Clay remaining in second place with 22.2% (1,370 cores).
- When CBRA recommended depths are achieved (i.e., >5.0 mbsf recovery), the dataset was reduced further to a subset comprising 467 cores. From this subset, layered soils of between 2 and >5 layers dominated significantly with 68.3% (319 cores) of the dataset, and single (non-layered) soil profiles only accounting for 31.7% (148 cores). In this scenario, Sand over Clay was the most common soil profile (26.8%, 125 cores), with single (non-layered) Sand coming second with 17.8% (83 cores) of the dataset.

It is clear from these results that, when low penetration samples are removed (i.e., those that only achieve <0.3 m recovery below seafloor), layered soil profiles comprising between 2 and >5 layers are a significantly common occurrence across the study area of the North Sea. As a result, it would be prudent to further investigate the impact of soil layering on anchor penetration depths in relation to Depth of Lowering assessments, as part of the overall CBRA process.

5.2 FURTHER WORK

Results from WP1 will be used to inform other project work packages which include:

- **WP2 (Physical Testing)**: Assess the penetration depth of existing anchor designs in representative soil horizons through advanced centrifuge physical modelling and 1G testing. Investigate the impact of disturbed (ploughed) zones on anchor behaviour.
- **WP3 (Numerical Modelling)**: Develop a MPM-based digital design environment to assess the penetration potential of existing and new anchor designs across a spectrum of soil conditions.
- **WP4/5 (CPT-Anchor penetration tool development & application):** Development of a CPT-based anchor penetration depth tool for diverse soil conditions via physical experimentation and advanced numerical modelling.
- **WP6 (Dissemination & CPT-anchor toolkit)**: Disseminate the outputs and findings to the industrial and research communities. Engagement activities beyond the wider supporting team, including a more-general end of project workshop focused on geotechnical risk in offshore renewable energy.

In relation to WP6, it is envisaged that the results and master Unitisation database that resulted from the endeavours of WP1 could be used to create geospatial products (e.g., GIS maps/layers) that would be of use to the subsea cable installation community. An example of this is presented in **Figure 24**, which shows quantitative average shear strength (s_u) values for specific depth ranges of 0.0-0.5 and 0.51-1.0 m below seafloor, mapped across the Witch Ground Basin area of the North Sea.

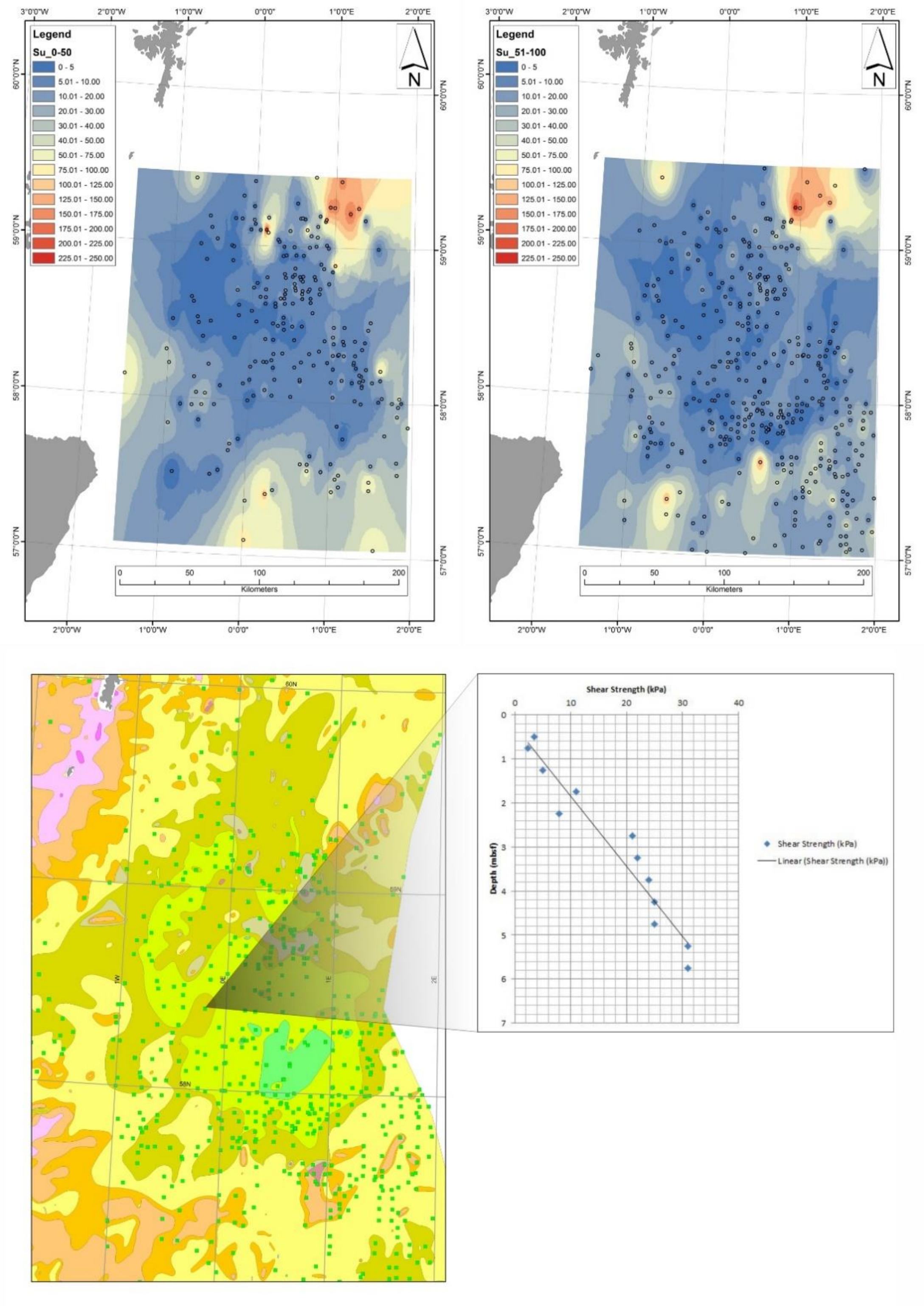


Figure 24 Contoured average shear strength maps for depth ranges of 0.0 - 0.5 m (top left) and 0.51 - 1.0 m below seafloor (top right). Colour ramp shows distinct shear strength ranges in kPa values. Bottom image shows a shear strength profile for a single core taken from the Witch Ground Basin, North Sea, overlain on top of the 1:250,000 Seabed Sediments map. Contains OS data © Crown copyright and database rights 2024.

Glossary / Acronyms

BGS – British Geological Survey

CBRA – Cable Burial Risk Assessment

CPT – Cone Penetration Test

DEA – Drag Embedment Anchor

DoL – Depth of Lowering

D_r – Relative Density (granular soils)

DU – Durham University

EPSRC – Engineering and Physical Sciences Research Council

GC – Gravity Core

GS – Grab Samples

mbsf – metres below seafloor

OWF – Offshore Wind Farm

S_u – Shear Strength (cohesive soils)

UoD – University of Dundee

UK – United Kingdom

UKCS – United Kingdom Continental Shelf

UKRI – United Kingdom Research & Innovation

VC – Vibrocore

WP1 – Work Package 1

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