CPT interpretation in marine soils less than 5m depth – examples from the North Sea

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ABSTRACT: This paper examines the interpretation techniques used in shallow offshore geotechnical surveys, with particular emphasis on cone penetration testing (CPT) and its use as a tool for providing adequate information for the analysis of soil conditions. This will include highlighting some of the key issues that need to be considered when interpreting the data, such as the relevance of friction and pore pressure ratio. The interpretation techniques for review are those within 5m of the soil surface using seabed frame units and a standard 10cm^2 piezocone (position u_2). The paper presents case studies from Bolders Bank Formation (Southern North Sea) and Witch Ground Formation (Northern North Sea). Particular attention is given to CPT locations where core samples are available close by to allow correlation.

1 INTRODUCTION

Geotechnical testing of shallow seabed soils is typically required for pipeline and cable route surveys. The soil parameters required are used in pipeline engineering such as determining pipeline/soil interface friction properties and upheaval buckling resistance of backfill soils. In addition, testing is required for input into trenching assessments for both cables and pipelines.
The general requirements for shallow geotechnical surveys include:

- Insitu testing using empirical correlations, typically using cone penetration testing (CPT) equipment. These are used for detailed soil stratification and determination of a number of engineering parameters.
- Sampling, generally using coring techniques to allow material identification and determination of a wide range of engineering parameters from laboratory testing.

The specific methods are generally chosen based on predicted soil conditions, to achieve best penetration or recovery and least sample disturbance. From the author's experience, both CPT and coring techniques have value in determining accurately the required information needed for engineering and soil classification parameters. Both, recovered soil samples and CPT data give a much greater confidence level, if used properly. However, it is important to include seabed sampling as part of any geotechnical survey as some engineering parameters are only achievable by laboratory testing of soil samples. For most surveys, it is also standard to use the logged cores as a check against CPT interpretation. It is apparent from the examples in this paper that they do not always correlate perfectly.

This paper does not aim to produce a new or modified model of CPT data interpretation, but emphasizes some of the problems that exist with interpretation with respect to data quality, data manipulation and the use of existing models, with specific regard to fine layering and non-uniform soils.

1.1 *Required Parameters*

The Guidance Notes on Geotechnical Investigations for Marine Pipelines (2004) outlines the suitability of the CPT for defining certain soil parameters. This is summarized below:

Table 1. CPT soil parameter suitability

Soil Parameter	**SAND**	**CLAY**
Soil classification	Good	Good
Soil density	Poor	Good
Soil strength (standard CPT)	Poor	Good
Soil strength (T bar)	N/A	Excellent(soft clay)
Friction angle	Good	Excellent
Sensitivity	N/A	OK
Consolidation (dissipation)	Excellent	Moderate
Permeability (dissipation)	Excellent	Moderate

2 INTERPRETATION OF CPT DATA

Interpretation of the CPT data has become more of a mathematical exercise, with the introduction of graphical models from various authors, which all differ from one another. Proprietary and bespoke software has been written to provide automatic soil profiles based on existing models. Soil classifications have been developed and refined using one or more measured parameters including cone tip resistance, friction ratio, and pore pressure. The key signatures to look for in measured CPT data are summarized below:

Table 2. Key CPT Interpretation parameters

Soil Type	**Cone Resistance**	**Side Fiction**	**Pore Pressure**	**Friction ratio**
Soft to firm CLAY	Low	Low to medium	Positive	Medium to high
Stiff to hard CLAY	Medium	High	High Negative	High
Soft SILT	Low	Low to medium	Negative / ambient	Low to medium
Stiff to hard SILT	Medium	High	High Negative	High
SAND	Medium to high	Low	Ambient	Low
Loose, silty SAND	Low to medium	Low	Negative to ambient	Low
Dense, silty SAND	High	Medium	Negative to ambient	Low
Shell / GRAVEL	High – spikey	Medium to high	Negative	Medium
Organic Material	Low to medium	High	Positive and negative	Very high

It is important to look at the shape of the individual curves to see what the trends are; increasing or decreasing and at what rate this occurs. Some curves may remain relatively constant.

Everybody has a slightly different way of interpreting CPT data, even when models are available. The main variances occur with the fine detail, particularly where local knowledge may have a bearing. It is essential that all knowledge and data is available to all parties, when finalizing CPT profiles.

2.1 *Existing models*

The most frequently used models are those proposed by Robertson (1990). Ramsay (2002) revised these models based on correlation with samples taken from the North Sea. In general, these are acceptable for the generalization of soil profiling, however they do not take into consideration the fine layering of soils or the presence of gravel/shell. This finer detail may be very important when looking at soil parameters for trenching or cable-laying. One concern is the use of friction ratio in determining this layering; however the use of pore pressure ratio may be more effective.

2.2 *Cross Correlation Function (CCF)*

The process of CCF enables two data sets to be compared and determines the position of strong correlation. With regard to evaluating the Friction Ratio (F_R) parameter for soil classification, it is important that the measured values of q_c and f_s are shifted relative to one another because of the physical offset between the cone and the friction sleeve. CCF is discussed further within a paper by Jaksa et al (2002), and showed that the acceptance of fixed friction offsets of between 75-100mm (Robertson & Campanella, 1983), may not be applicable to all soils, when using the interpretation models. The other methods used can be done manually by eye to try and match up the peaks and troughs or apply no correction at all. The process of CCF, attempts to establish a strong relationship between the cone end resistance and the side friction to determine what the shift distance for the friction should be. The authors found that in the case of heavily interbedded deposits, the CCF technique should be adopted.

3 EXAMPLES FROM THE NORTH SEA

3.1 *Background setting*

Two marine sites have been selected to demonstrate the use of the cross correlation function and interpretation of shallow marine soils. The two sites are situated in the North Sea, one in the south, where the soil is predominantly stiff CLAY (Bolders Bank Formation), the other in the north, where the soil is composed of loose to medium dense SAND (Recent) and very soft SILT and CLAY (Witch Ground Formation).

3.1.1 *Southern North Sea*

The Bolders Bank Formation characteristically consists of reddish to grayish brown, stiff diamictons that are generally massive, but in places possess distinct, commonly arenaceous layering and deformational structures. The majority of its pebbles are derived from the sedimentary rocks of the east coast and is dominated by chalk (BGS – The Geology of the Southern North Sea, 1992). These deposits are typical Devensian glacial morainic sediments, and have been subjected to over consolidation by ice loading.

3.1.2 *Northern North Sea*

The Witch Ground Formation is a late Weichselian to Holocene marine deposit, composed primarily of very soft silts and clays, with an increase in sand content to the basin edge. This formation is slightly younger than the Bolders Bank. The area chosen consisted of loose and soft sediments of interbedded silts, clays and sands.

3.2 *Cross Correlation Function Analysis for Friction*

3.2.1 *Cross Correlation Function Analysis – Witch Ground*

There were a total of 27 CPTs carried out along a pipeline route survey in similar soils of inter-bedded clays, sands and silts; of these, 10 needed no correction, 9 showed a CCF of 2cm, 4 showed a CCF of 4cm and 4 showed no correlation.
There was some correlation along the route where soils changed slightly and the friction shifts were grouped together.

3.2.2 *Cross Correlation Function Analysis – Bolders Bank*

There were a total of 24 CPTs carried out along a pipeline route survey in similar soils of stiff clays with chalk gravel content; of these, 9 needed little or no correction, 8 showed a CCF of greater than 6cm and 7 showed little correlation. There was no lateral grouping of similar CCF results.

3.3 *Problems with using pore pressure and friction ratio*

Friction and pore pressure ratio are unreliable when encountering gravels and shells, particularly in clay, producing unusual readings. The gravel may roll around the sleeve or in some cases push the base of the sleeve at the lip seal edge, where premature increase in sleeve friction may occur. In the worst case this may damage the sleeve or even overload the sleeve sensor. High negative pore pressures may occur due to temporary cavitation and may take some time to return to equilibrium. This will affect the readings for friction ratio. This will impact on the use of interpretation models. To use q_c in place of q_{net}, would be obvious, however this requires much re- processing of the data.

Surface soils – particularly the upper half metre may not react at all to friction in very soft or loose soils, which will lie in the sensitive fine grained zone of the models. This does not help interpretation. This upper layer is important for cable and pipe laying and trenching. The friction sleeve reaction may not be significant enough in layered soils to identify an accurate thickness of thin bands.

Eslami and Fellenius (2004) also produced an interpretation model based on using friction instead of friction ratio. They argued that, while both cone resistance and sleeve friction are important soil profiling parameters, plotting one as a function of the other may distort the information

3.4 *Correlation with soil sampling*

Comparison with adjacent cores assists greatly with CPT interpretation. However, the sampling techniques themselves have problems:

- The upper soft/loose layers may be pushed aside due to stronger tulips
- Rodding and plugging may miss out softer layers at depth
- Vibration may cause samples to bulk up and essentially shorten in length

3.5 *A worked example – Bolders Bank Formation*

The data shown here is from a pipeline route survey in the Southern North Sea. The soil conditions were manually interpreted as shown in figure 1.

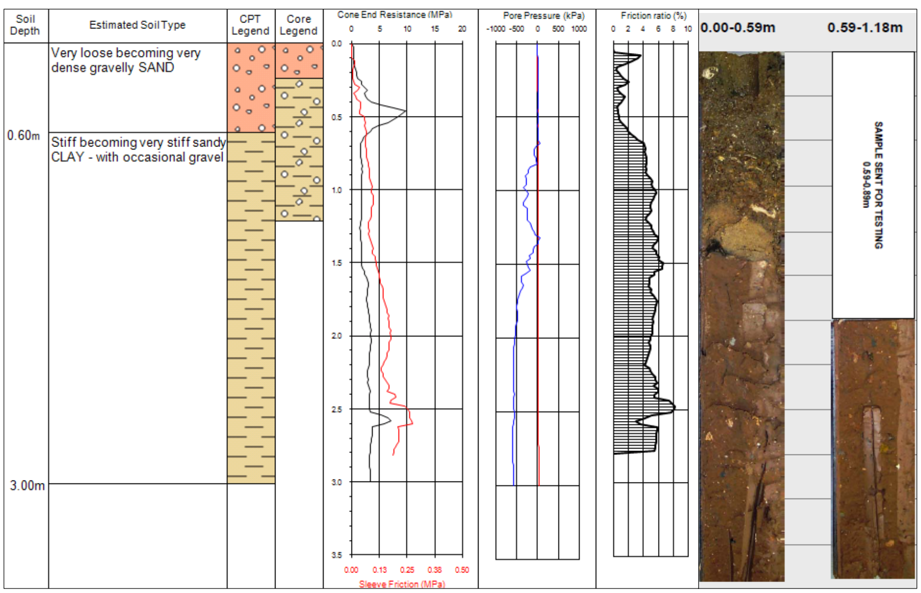

Figure 1. CPT and core results

- The core shows a surface layer of sand and gravel (probably re-distributed due to vibration) of 0.23m in depth.
- The CPT indicates a depth of 0.60m. The core shows a lot more gravel (albeit chalk) than the CPT indicates.
- The friction shift was predicted to be 10cm from the CCF analysis. This seems acceptable and in line with recommendations.
- The pore pressure is negative with no indication of returning to a positive state as suggested by the Robertson and Campanella (1983) models. The Ramsay (2002) model allows for this.

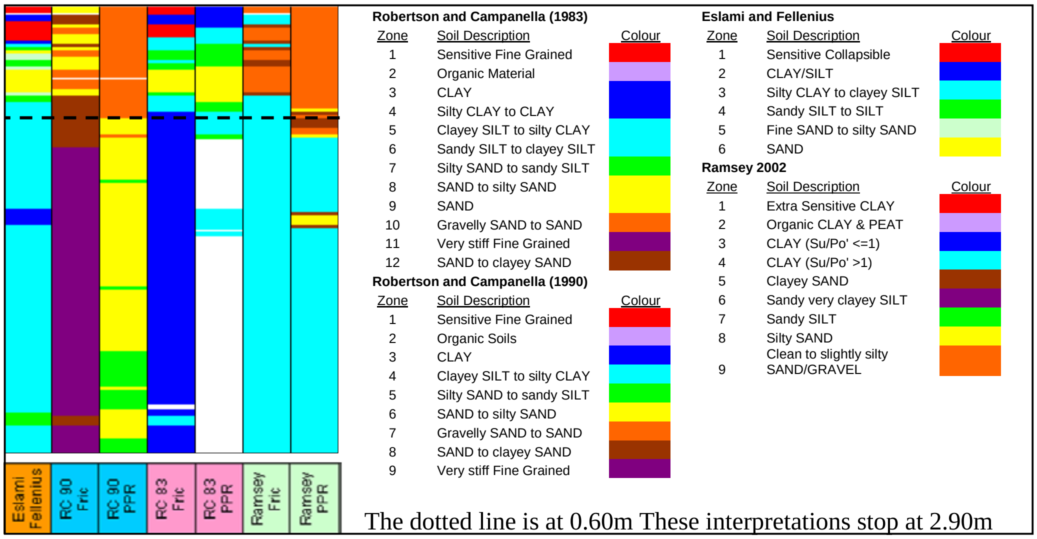

Figure 2 Soil interpretation models

Figure 2 shows the comparison of the different models being used for the above CPT. The models above all have slightly different interpretations for the soil indicated in Figure 1, and in one case the data lies outside the graph (Robertson & Campanella, 1983 Pore Pressure Ratio-PPR); this may relate to little offshore data being applied. The Robertson (1990) graph of PPR also mis-interprets as sand. In the cases of both these PPR graphs, gravel is not recognized. Ramsay (2002) recognizes gravel in all instances. Friction Ratio seems to give a better indicator of gravel in the upper layer.

3.6 *A worked example – Witch Ground Formation*

The data shown here is from a pipeline route survey in the Northern North Sea. The soil conditions were manually interpreted as shown in figure 3.

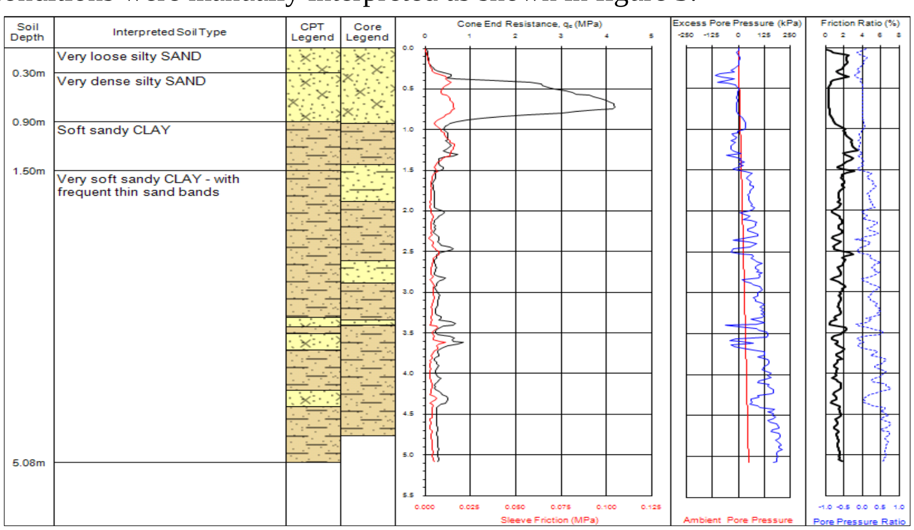

Figure 3 CPT and core results

- The core and CPT test results correlate very well
- The friction shift was predicted to be zero by CCF analysis, which does not comply with recommended standard.
- The CPT data may pick out more layering than core logging. The core was very uniform in colour and some mixing occurred, probably due to vibration.
- Pore pressure seems to pick out the thin layering much easier than the friction ratio. The pore pressure had good reaction

The models give similar results. The Robertson & Campanella (1983) friction and the Eslami & Fellenius (2004) plots show fine grained soil in the very soft clays, which is not as precise as the other models. Layering can be seen in all models, but not predicting sand too well. The Ramsay (2002) models seem to have the better interpretation.

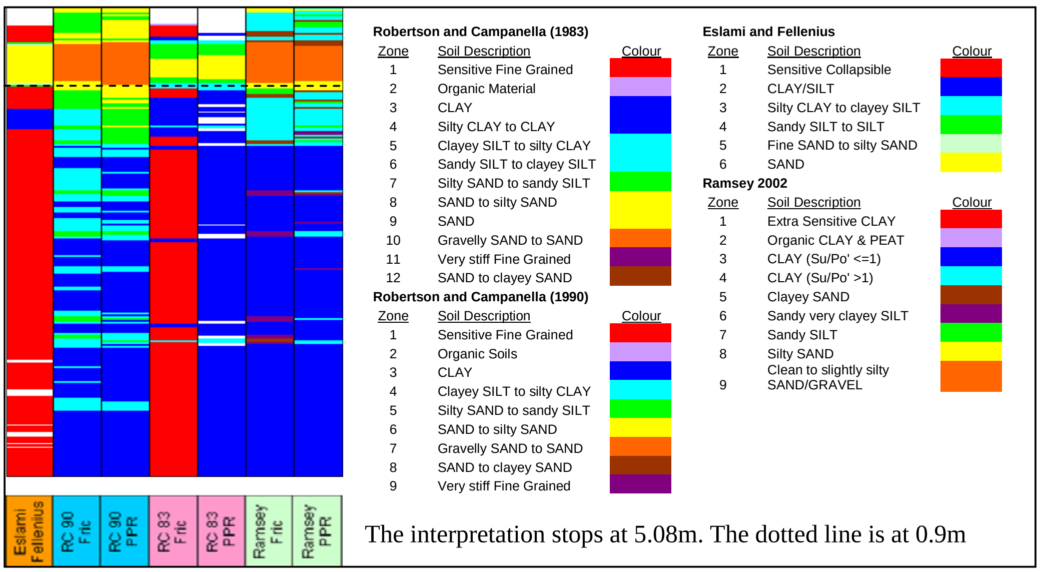

Figure 4 Soil interpretation models

4 CONCLUSIONS AND RECOMMENDATIONS

Based on the CCF results, there is a variable range of shifts that could apply to friction before manipulating the data in preparation for interpretation of the soils based on friction ratio. It is noted the acceptance criteria of 75-100mm works better in more uniform soils, however sometimes the CCF shows no correlation.

When interpreting marine soils it is noted the Ramsey (2002) model works better than the Robertson and Campenella (1983) models. This is likely to be due to the Ramsey (2002) model being devised and checked against off against offshore North Sea soils. The issue with the Robertson and Campanella (1983) model is that in marine soils the high negative pore pressure results lie outside the model.

When comparing CPT data to core logs, it should be noted that the depth determination of core samples can be unpredictable. These core samples are however, important to assist with the CPT interpretation. To be able to accurately determine the precise levels of soils within the CPT all data sensors within the CPT should be used by any experienced Geotechnical Engineer ideally with local knowledge, with all information made available to them. The CPT interpreter should use patterns of data, including shape and magnitude of cone resistance profiles to identify uniformity within layers. Local knowledge is paramount, particularly in soils that are not standard. Hard layering may be identified as cemented/ gravel or even bedrock. Simple, relatively inexpensive tools, such as coring and CPT testing may identify these without more expensive techniques, such as drilling, if it is fit for purpose.

In conclusion, more analysis of CPT data is required to be able to develop a precise model for global use in interpretation of soils. However it may be the case that project specific models may be the answer, allowing soil signatures to be applied to the CPT data.

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