Linking multi-sensor core logger data with in-situ and laboratory testing: A North Sea case study

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ABSTRACT

Driven by an increase in the scale of laboratory testing programs, the industry is looking for new methods of soil characterisation and ways to extract more benefit from existing data. In this paper, applications of Multi-Sensor Core Logging (MSCL) to site characterisation projects are discussed, highlighting the potential for providing a fast, quantitative assessment of recovered samples. Sensors of the MSCL include bulk density, *P*-wave velocity, natural gamma, electrical resistivity and magnetic susceptibility. Natural gamma is shown to be related to higher silt and clay content, acting as a useful parameter for soil classification and quantitative assessment of fines content. A comparison between MSCL and *in-situ* CPTu data reveals correlations between natural gamma and friction ratio, normalised soil behaviour index, Ic, and net pore pressure response. By collecting MSCL data on all samples at the beginning of a lab program, one can obtain a full overview of the material available for testing, leading to more strategic sample selection and a reduced overall volume of testing. Correlations with MSCL parameters and geotechnical properties can be used to predict continuous profiles, and be extended to in-situ measurements from borehole logging and CPT.

Keywords: Multi-sensor core logging (MSCL); natural gamma; cone penetration testing; laboratory testing.

1. Introduction

1.1. Multi-Sensor Core Logging

Geotechnical characterization of the subsurface for the energy sector remains time-consuming, expensive, and challenging. In the current market with the boost of offshore wind developments, onshore laboratory testing programs are growing in size and duration, causing delays across projects. At the same time, there is motivation for offshore wind projects to reduce costs without increasing risk. Hence, the use of alternative techniques of soil characterisation to reduce the volume of time-consuming geotechnical laboratory testing is desired. A viable alternative is, for instance, the Multi-Sensor Core Logging (MSCL) technique.

MSCL is a non-destructive technique used to collect automatic, continuous measurements with widespread use in marine geohazards research, paleoclimate and mineral exploration, or geotechnical investigations (e.g. Weber et al., 1997; Vatandoost et al., 2008). The MSCL has a modular configuration of sensors that include, but are not limited to, attenuated gamma density (analogous to bulk density), pressure and shear wave velocities (*P*- and *S*-waves), natural gamma, electrical resistivity and magnetic susceptibility (see Table 1). Measurements can be performed on lined soil samples or unlined rock samples.

So far, there are limited published examples of MSCL being used in offshore geotechnical site investigations (e.g. Shreeve et al., 2017; Coughlan et al., 2023). Though, the ability to relate geotechnical properties to continuous geophysical profiles is an attractive prospect and can not only help to better plan laboratory testing but reduce the total volume of testing required and reduce the uncertainty in measured and interpreted geotechnical soil properties. Typical applications of MSCL for geotechnical site investigations are outlined in Table 1.

1.2. Natural Gamma

Of the MSCL sensors, natural gamma may be of particular use to geotechnical site investigations. Since natural radioactivity is concentrated in silts and clays compared to sands, natural gamma can be used as an indicator of silt and clay content (e.g. Ayres & Theilen. 2001). Natural gamma is a measurement of electromagnetic radiation emitted by radioisotopes such as potassium (^{40}K), uranium (^{248}U), thorium (^{232}Th) and their derivatives, commonly found in clay minerals. Natural gamma can be expressed as total, i.e. the sum of gamma radiation or spectral, which provides a full energy distribution reading for K, U and Th, and can be used to improve estimates of clay mineralogy (e.g. Klaja & Dudek, 2016). Natural gamma discussed in this paper refers to total natural gamma, unless otherwise specified.

Natural gamma from wireline borehole logging has been used for decades in hydrocarbon exploration to identify changes in lithology, yet there are few examples of this application to geotechnical site investigations (e.g. Cripps & McCann, 2000; Lafuerza et al. 2006), likely due to the cost-effectiveness of alternatives such as cone penetration test (CPT). Wireline logging for offshore site investigations is typically for the express purpose of measuring in-situ *S*-wave velocities to calculate the shear

Table 1. Multi-Sensor Core Logger (MSCL) sensors and key notes relevant to geotechnical site investigations.

Sensor	Relevance to Site Investigations
Attenuated Gamma Density	Analogous to bulk density. Calculate unit weight, porosity, and water content.
Natural Gamma	Quantitative indicator of silt and clay content. Core-to-borehole correlation with downhole natural gamma wireline logs. Spectral natural gamma can give more detail on clay mineralogy.
P-wave velocity and attenuation	Related to lithology, saturation ratio and sample quality. Calculate acoustic impedance from P-wave velocity and bulk density. Accurate P-wave velocity measurements are an important input to seismic data processing and modelling.
S-wave velocity and attenuation	Calculate G_{max} from S-wave velocity and bulk density. (Note sensor only available for unlined rock samples.)
Electrical Resistivity	Related to porosity and permeability. Sensitive to saturation ratio and so can be used to assess drainage of sand.
Magnetic Susceptibility	Related to mineralogy, magnetic susceptibility can be useful for unitisation and correlating samples across the site.

modulus, *G*. Caliper logging is done as a prerequisite to assess the borehole condition, with a natural gamma tool commonly run simultaneously. This means that natural gamma is one of the most common wireline logging measurements, yet they are not often quantitatively assessed. One advantage of natural gamma logs is that they are continuous, and so can be used to predict soil properties in zones of low sample recovery.

The limited literature on natural gamma in geotechnical site investigations provides promising correlations. In his study using both CPTu tests and natural gamma borehole logs, Schiltz (2020) highlighted a close relationship between normalised soil behaviour type index, Ic, and natural gamma, commenting that this relationship improved the recognition of different units across the site. Natural gamma has also been quantitatively related to geotechnical properties such as density, silt and clay content, and undrained shear strength for normally consolidated clays (e.g. Ayres & Theilen, 2001; Lafuerza et al., 2006). Furthermore, sedimentological interpretation of natural gamma logs can also provide information on depositional environment, useful for developing geological models (e.g. Mondol 2015, Schiltz 2020).

Berthet et al. (2021) identified natural and spectral gamma ray sensors as high potential add-ons to cone penetration testing, with a technology readiness level of 5-6 (technology demonstration). Indeed, gamma CPT cones are commercially available and are used onshore for example to distinguish between clay and weathered chalk (In situ SI, 2024). However, validation and wide acceptance of these sensors offshore will require a database of CPT profiles with complementary in-situ and laboratory measurements (Berthet et al. 2021). To that end, MSCL is well suited to contribute to relevant databases.

In this paper, we demonstrate some of the applications of MSCL data to geotechnical site investigations with selected examples from the Central North Sea. We highlight natural gamma as a particular parameter of interest and suggest that MSCL is an effective method of estimating index properties, thus reducing the volume of destructive geotechnical testing required.

2. Methodology

In-situ testing, sampling and index tests were conducted at two different sites in the Central North Sea in 2023. Sampling included push piston downhole sampling and vibrocore sampling. Selected samples were retained in their plastic liners and sent to the Norwegian Geotechnical Institute's (NGI) onshore laboratory for MSCL and further geotechnical testing. MSCL data was collected on samples with a measurement interval of 1cm using the Geotek Ltd. MSCL-S system. Logging was completed with the sample as received, i.e. inside the liners and with no sample preparation needed.

Natural gamma was measured by three scintillation detectors as part of the MSCL system with a recording time of 10s per measurement. Total natural gamma is calculated as the total gamma radiation recorded during the measurement period minus the background reading. Natural gamma measurements are presented as raw counts per second rather than the standard unit of API. Counts per second is proportional to the sample volume, so measurements on vibrocore samples, with a surface area 1.5 times larger than the lined Shelby tube samples, were divided by 1.5 in order to allow direct comparison of values. Following MSCL, a comprehensive geotechnical laboratory testing program was conducted.

Samples were extruded, described and post-processed. Laboratory tests included particle size distribution (PSD) tests with sand content were determined by wet sieving (ISO 17892-4, 2016), while silt and clay content obtained by the falling drop method (Moum, 1965). Samples were classified into major soil types and units with a combined interpretation of in-situ testing, sample description and index test results.

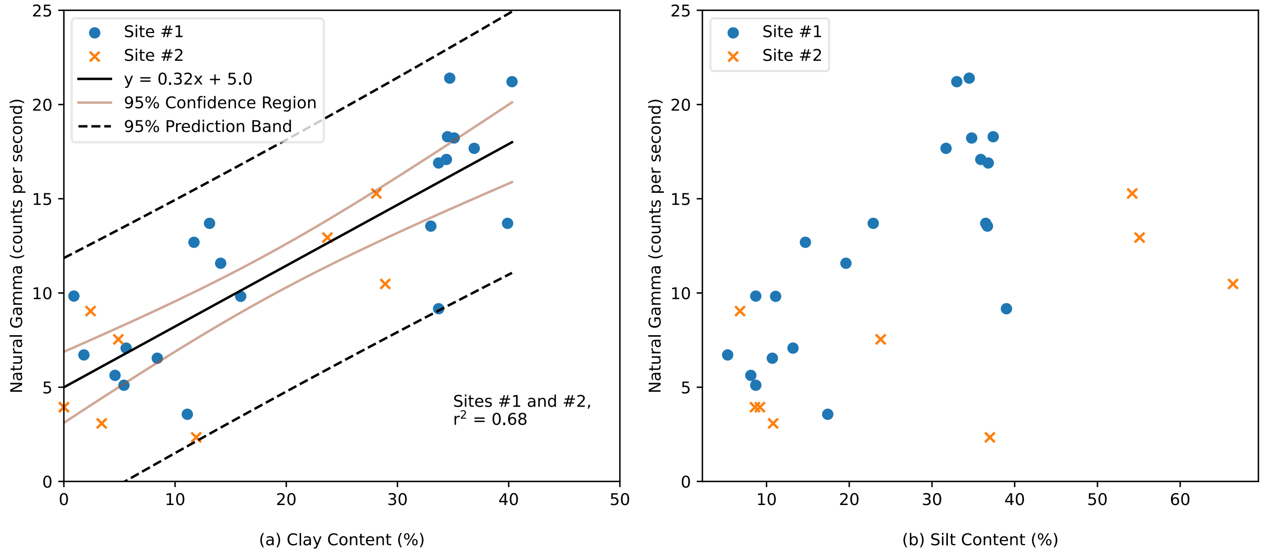

Figure 1. Natural gamma against (a) clay content and (b) silt content. Data from sites #1 and #2.

3. Results and Interpretation

3.1. Natural gamma – clay content, plasticity

Natural gamma varied between 2 and 23 counts per second, with a general trend of increasing with clay content at both sites #1 and #2, with a coefficient of determination, r^2, of 0.68 (Fig. 1a). Since both sites #1 and #2 fit the same trends of increasing with clay content this suggests that the clay mineralogy is similar between the two sites.

Higher natural gamma also correlates with higher silt content (Fig. 1b), though there seems to be different trends between sites #1 and #2. The complete particle size distributions are shown, for reference, in Fig. 2. For site #1, with a silt:clay ratio of close to 1:1, the trends of natural gamma against silt and clay content are similar, and the contribution of silt or clay particles to the total natural gamma measurement cannot be distinguished. In comparison, for site #2, the silt:clay ratio is in general higher, between 2:1 and 5:1. Increasing silt content at site #2 corresponds with comparatively lower natural gamma measurements, since higher silt content is decreasing the proportion of clay content. Then, at site #2, it is suggested that clay content is contributing more to the natural radioactivity of the samples. From these observations, it seems that total natural gamma is a more reliable indicator of clay content, and the silt content can be estimated if the silt:clay ratio is known.

Plasticity index, Ip, increases linearly with clay content, with a coefficient of determination, r^2, of 0.87 (Fig 3). Note that Fig. 3 includes data on additional samples that were not run through the MSCL, but they are from the same geotechnical units.

3.2. Unitisation and comparison of MSCL with CPT

At site #1, in-situ testing and offshore sample descriptions were used to classify vibrocore samples into different soil types and units (Table 2). The liners were then run through the MSCL, and a comparison between MSCL, CPT parameters and units can be made.

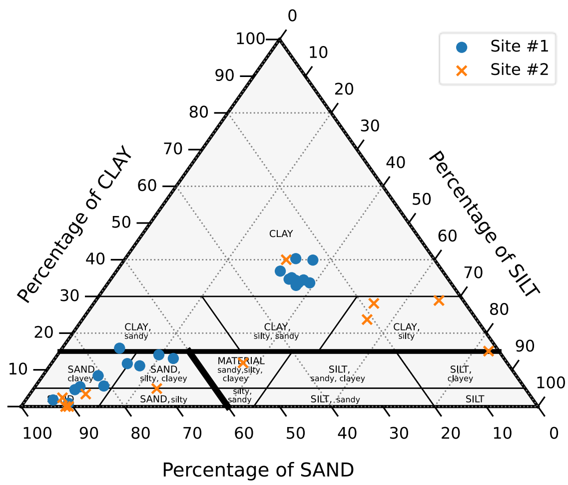

Figure 2. Soil classification triangle based on particle size distribution of samples from sites #1 and #2.

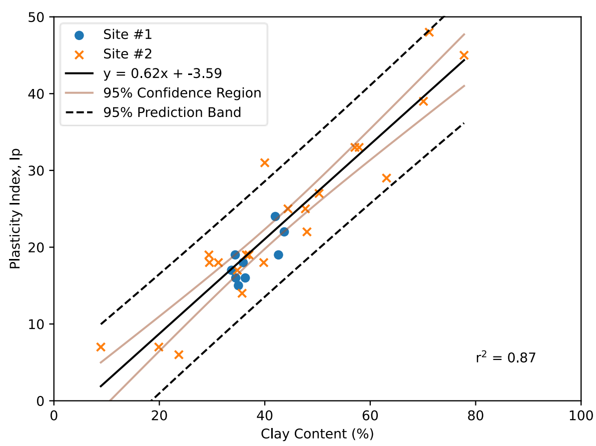

Figure 3. Plasticity index, Ip, against clay content (%). Data from sites #1 and #2.

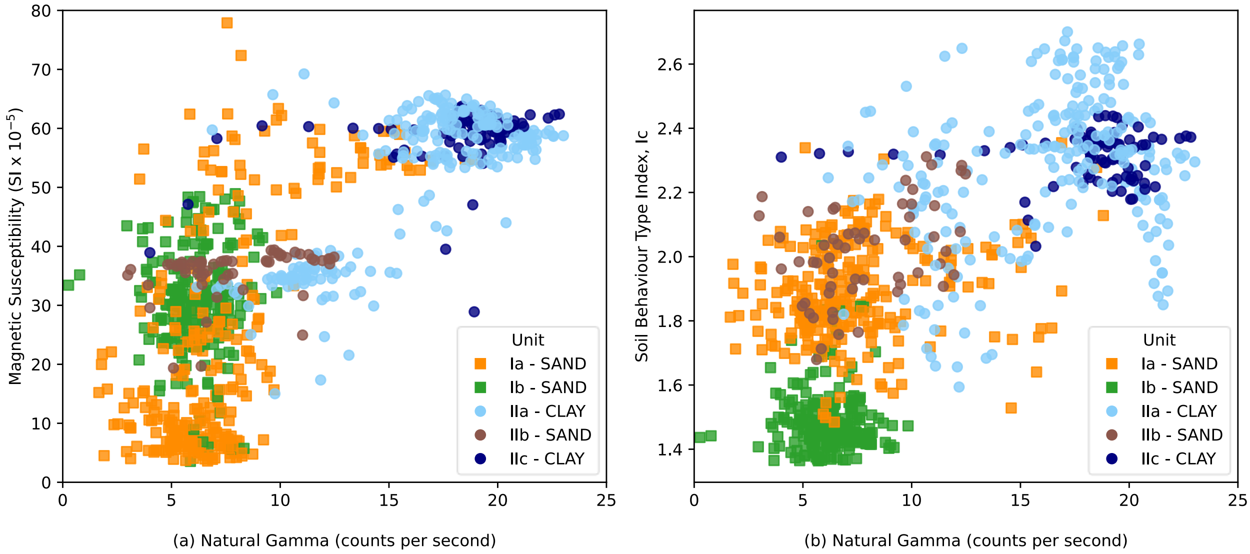

Figure 4 Site #1 - Natural gamma against a) magnetic susceptibility, also from MSCL, and b) normalised soil behaviour type index, Ic, from CPTu tests. Units determined from CPT and offshore sample descriptions.

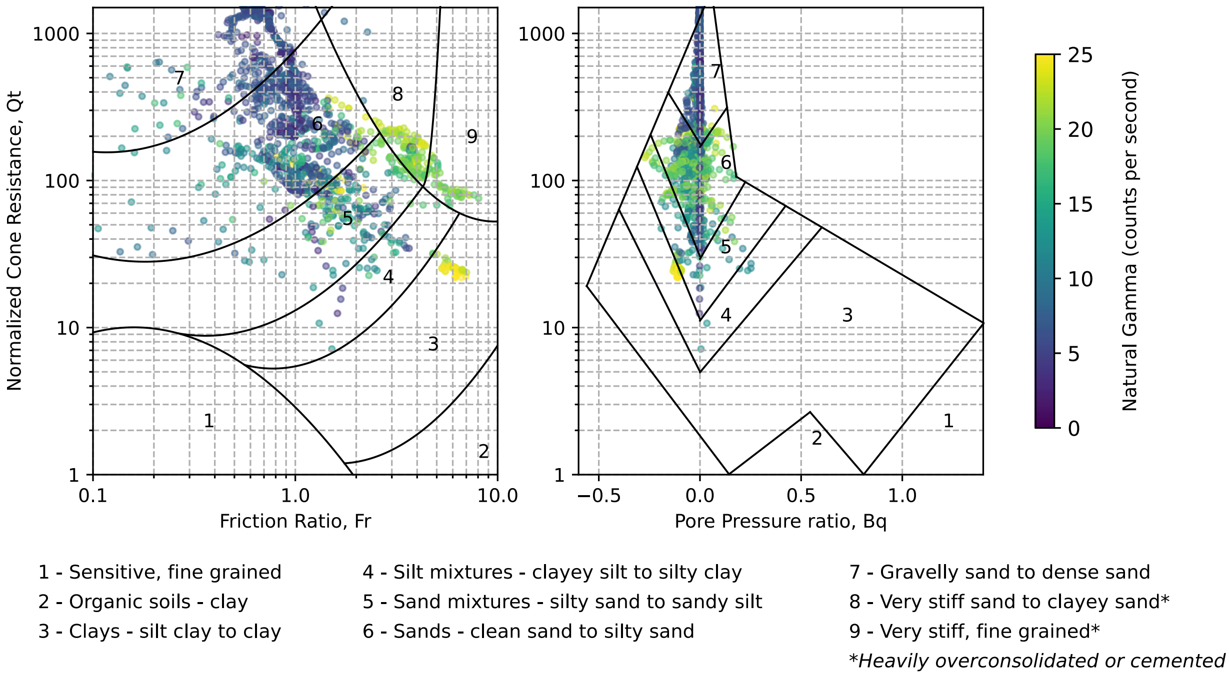

Figure 5 Soil behaviour type (SBT) charts (Robertson, 1990) coloured by natural gamma as measured with the MSCL on recovered samples. Data from sites #1 and #2. The distance between CPT and borehole locations is approximately 5m.

Table 1. Description of units at Site #1

Unit	Description
Ia	SAND, loose to medium dense, with silt
Ib	SAND, medium dense to dense
IIa	CLAY, high to very high strength, with layers of silt and sand
IIb	SAND, dense, with layers of clay
IIc	CLAY, high to very high strength

In general, sand units (Ia, Ib, IIb) have lower natural gamma, between 0 and 10 and lower magnetic susceptibility, below 50 x10^{-5} SI (Fig. 4a). The sand-rich unit I can be sub-divided into units Ia and Ib by differences in magnetic susceptibility (0 – 20 x10^{-5} SI, 20-50 x10^{-5} SI) and soil behaviour type index, Ic (1.3 – 1.6, 1.6 – 2.1, see Fig. 4b) which reflects the difference in silt content (see Table 2).

Compared to unit I, the clay-rich unit II generally has higher natural gamma (5 – 20) and higher Ic (> 2.1) (Fig. 4). Scatter in the plots reflects changes in soil type, for example unit IIb has a higher sand content.

Robertson (1990) soil behaviour type (SBT) charts are shown with data from sites #1 and #2 (Fig. 5), coloured by natural gamma as measured by the MSCL. Higher natural gamma corresponds well with higher friction ratio and net pore pressure response. From zones

3-7, covering the range from clays to clean sand, there is a trend of decreasing natural gamma (Fig. 5a). Zones 8 and 9, corresponding to heavily over-consolidated material show high natural gamma values, between 15 and 23.

4. Discussion

The information gained from MSCL can be used to improve the planning of lab testing and reduce the total volume of testing required, which can lead to faster lab programs. For example, and as discussed above, MSCL can quickly provide information about the soil PSD. This can save significant time not only by reducing the number of PSD tests, but since PSD tests are a prerequisite for creating sand batches, classification supported by MSCL can also lead to faster batching and following advanced testing.

An integrated approach combining MSCL, laboratory testing, *in-situ* CPTu tests and wireline logging has the potential to extract more benefit from routinely collected data. A clay/silt-natural gamma relationship can be derived with MSCL and laboratory testing, as demonstrated (Fig.1), and be applied to in-situ measurements such as wireline logging or gamma CPT to quantitatively assess the fines content and improve predictions of soil type. Similarly, correlations between natural gamma and CPTu tests could be derived from boreholes with both natural gamma wireline logs and downhole CPTu data.

By comparison of MSCL data with adjacent CPTu data, one could derive site-specific CPTu correlations to improve the prediction of soil properties at locations or depth intervals with only CPTu data. This can lead to reduced uncertainties in soil type, reduced risk and improved allocation of resources for further site investigations.

Further work could take full advantage of the MSCL capability of measuring spectral natural gamma to estimate relative abundances of potassium, uranium, and thorium. Spectral natural gamma measurements require a longer measurement time, but strategic collection of these measurements would add significant information on clay mineralogy (e.g. Klaja & Dudek, 2016), fundamental to our understanding and effective use of derived relationships between total natural gamma, silt/clay content and plasticity.

5. Conclusions

In this paper, the applications of MSCL to geotechnical site investigations have been discussed. Relationships between MSCL, laboratory and *in-situ* CPTu testing have been presented for two North Sea sites. Based on the analysis of the data presented, the following conclusions can be made:

- Multi-Sensor Core Logging is a fast, reliable, and non-destructive method that can aid in the quantitative assessment of geotechnical soil samples. Data from the MSCL can be used to characterize and group samples together into units, which helps in the planning of laboratory testing programs, and can ultimately reduce the volume of testing required.
- In our dataset, total natural gamma is a quantitative indicator of clay and silt content. Silt content may be estimated if the silt:clay ratio is known. Higher natural gamma measurements also correlate with higher plasticity index, through the common relation of clay content.
- Natural gamma correlates with soil behaviour type index, Ic, and Robertson SBT charts. MSCL provides complimentary information to *in-situ* CPTu testing and is well suited to contribute to databases of CPTu profiles against geophysical properties.

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