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Using drilling data to derive geotechnical properties of variably cemented materials

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ABSTRACT

Geotechnical site characterisation of variably cemented material is often challenging due to lack of data. Drilling data is routinely measured as a part of standard geotechnical site investigation and can provide an alternative method to derive continuous ground profiles with depth. This paper examines the use of drilling data for site characterisation purpose. Based on the drilling data obtained from an offshore windfarm project site, where variably cemented materials were found, it is shown that the borehole specific energy calculated using the drilling data reasonably captures the variation in material types with depth. Also, the results show that borehole specific energy can be correlated with the laboratory test data in a similar manner to cone penetration test. Based on the results obtained from different locations covering a range of material types and in-situ state conditions, generalised relationships between different geotechnical parameters and borehole specific energy are presented. An example of how the generalised relationships developed using borehole specific energy can be used to derive design profiles for a selected site is also shown. The data and interpretation approach presented in this paper provide a useful guide for how the drilling data can be used to assess the continuous ground profile for variably cemented sites where only limited or no in-situ test and intermittent sampling data are available.

Keywords: cemented material, site variability, drilling parameters, specific energy, geotechnical parameters.

1. Introduction

Offshore sediments found in shallow water locations may comprise variably cemented materials (intact to weathered rock, such as chalk, mudstone, calcarenite). These materials are significant for offshore developments such as offshore wind farms and offshore energy projects. However geotechnical characterisation of these materials is often challenging as:

- It is difficult to obtain continuous in-situ test data (e.g. cone penetration test, CPT profile) and push tube/piston sampling data due to refusal in cemented materials/hard layers.
- Rock coring is often problematic due to highly weathered and variable nature of these materials. The sample recovery is generally low and often include poor quality fragmented/disturbed samples.

Sites featuring variably cemented materials are typically characterized based on laboratory test data obtained at intermittent depth. This approach does not provide continuous data and may be insufficient to capture the engineering characteristics of all key layers that may be critical for engineering purposes. In many cases, an insufficient amount of data is gathered during the geotechnical SI on variably cemented materials, which is not sufficient to properly derive the geotechnical parameters required for design purposes (Graham et al. 2013).

Borehole specific drilling parameters are routinely measured during geotechnical site investigation. This includes continuous measurement of feed force, rotary torque, penetration rate and rotation speed during different stages of borehole drilling operations i.e. installation of casing, wash boring, penetration testing, and rotary coring. These parameters can be adjusted depending on the ground condition, and continuous measurement allows the inherent variability of the subsurface to be captured. Despite this, drilling data is generally used for operational purposes only and is rarely considered for geotechnical site characterisation.

Several recent publications (e.g. Rodgers et al. 2020, Smith et al. 2015) and the authors' experience on commercial projects indicate that drilling data can be a useful guide to derive continuous soil profiles for variably cemented sites where there is a lack of sampling and in-situ test (e.g. CPT) data.

This paper investigates the use of drilling data for site characterisation purposes on variably cemented materials. Based on the drilling data obtained from an offshore windfarm project site, it is shown that the specific energy calculated using the drilling data can be correlated to geotechnical parameters in a similar fashion to in-situ tests (e.g. CPT). An example of how the specific energy profiles derived from drilling data can be used to derive the geotechnical design profiles for different parameters is also shown in this paper.

It should be appreciated that the correlations and proposed profiles presented in this paper are based on project specific data and their use for other projects may need to be verified using site-specific data.

2. Drilling Data

2.1. Project background

The drilling data presented in this paper were recovered as part of an offshore windfarm project located off the coast of North Norfolk in the UK, in water depths ranging between approximately 15 m and 25 m. The geotechnical site investigation was carried out using Benthic's 2nd generation Portable Remotely Operated Drill (PROD2) and included in-situ CPT, piston, and rotary core sampling. Drilling data was also measured as a part of the site investigation following similar methods discussed in Smith et al. (2015).

The general geology of the site included Quaternary sediments overlying Cretaceous chalk (Cameron et al., 1992; Mortimore and James, 2015). In this paper the drilling data from the Chalk units are discussed.

2.2. Drilling Data

The following drilling parameters were measured as a part of the geotechnical site investigations:

- Bit weight (kg)
- Rotary torque (Nm)
- Rotary speed (rpm)
- Rate of penetration (m/s)
- Drill water pressure (kPa)
- Drill water flow (L/min)

The drilling parameters were logged electronically at an interval of approximately one data point per second. The data was collected during all stages of the drilling operation. However, only the drilling data collected during the rotary coring stages of the borehole on the Chalk unit has been presented in this paper. The drilling water pressure and water flow were measured for operational purposes; however, these data were not used for calculation of borehole specific energy.

Fig. 1 shows an example of drilling parameters varying with depth, which portray the offshore operations and the variability of the in-situ material. To stop drilling and enable CPT push, the operator increases the bit weight to reduce rotation, as seen at depths of 31 m, 42 m, and 46 m, where the bit weight increases past 30 kN. The operator has targeted fixed rotary speeds between 400 and 450 rpm for the depth intervals plotted, with the horizontal fluctuation of approximately +/- 20 rpm caused by the tolerance of the sensor. The remaining variation in the drilling parameters, and hence the drilling energy, is reflective of the change in material type with increasing depth. The energy required to drill through the subsurface corresponds to the varying strength and density of the material present.

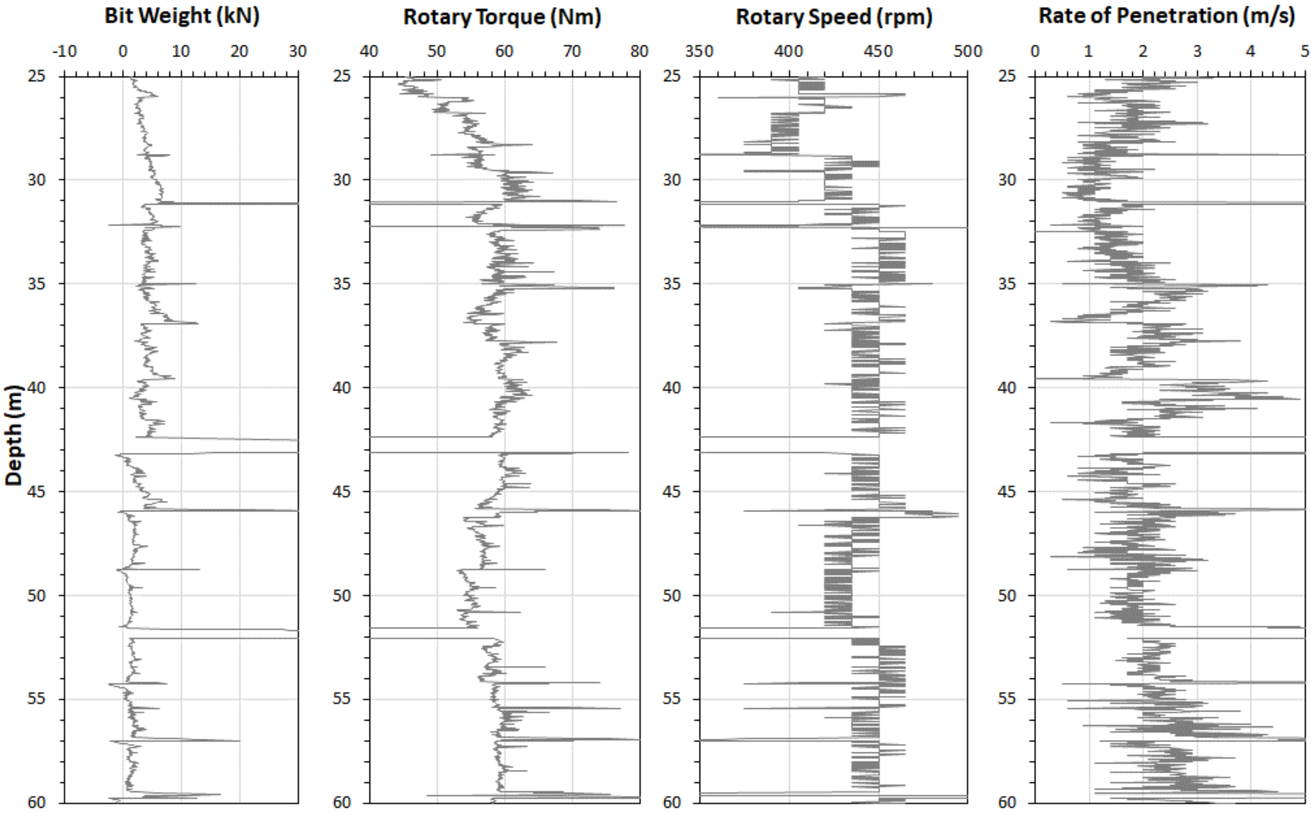

Figure 1. Example of measured drilling data with depth for BH-10

2.3. Drilling specific energy

The drilling data can be used to calculate the specific energy using the following equation proposed by Teale (1965):

$$\text{BSE} = \frac{F}{A} + \left(\frac{2\pi}{A}\right) \times \left(\frac{NT}{P}\right) \qquad (1)$$

Where, BSE = borehole specific energy (MPa), F = feed force - often referred to as bit weight (N), A = cross-sectional area of the drill hole (mm^2), N = Rotation speed (rpm), T = rotary torque (N-mm), and P = penetration rate (mm/min).

Fig. 2 shows the specific energy profile derived using Eq. (1) and the drilling data shown on Fig. 1. Also shown on Fig. 2 is the borehole log developed based on visual inspection of the samples for comparison purposes. In general, the specific energy profile captured the soil variability with depth.

Note that the average BSE profile shown on Fig. 2 is a simplified profile derived by averaging the data at approximately 20 mm intervals, which was used to compare with the laboratory test data in the following sections.

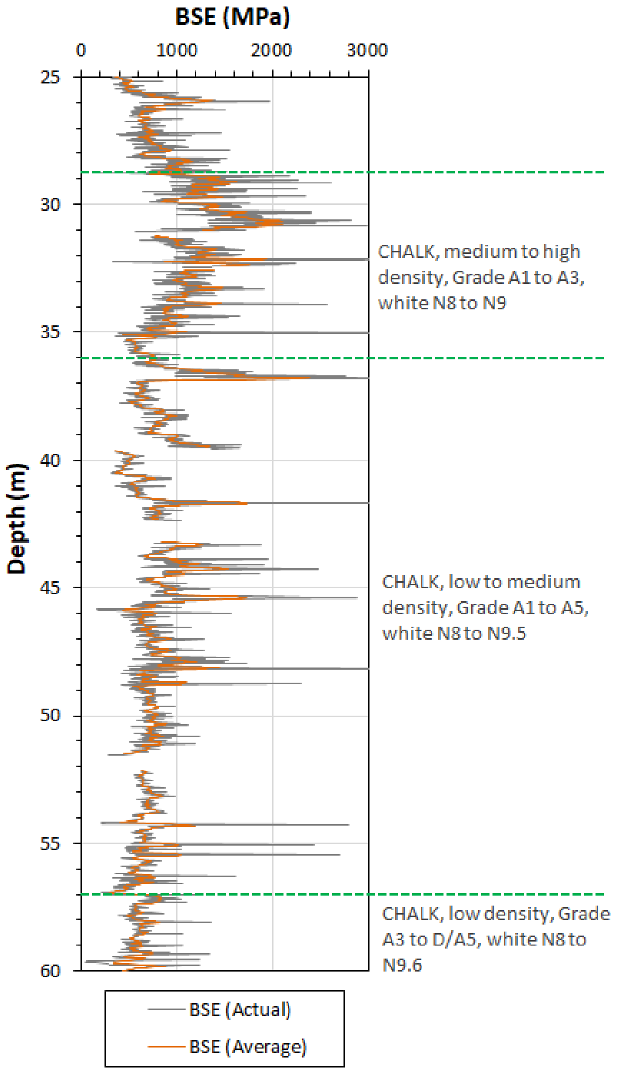

Figure 2. Borehole specific energy profile for BH-10

3. Correlations With Geotechnical parameters

The borehole specific energy profile has similar characteristics to cone resistance profiles in the sense that it reflects the material variability and provides a continuous profile with depth. Therefore, it is advantageous to correlate BSE with different geotechnical parameters for engineering use. To examine the suitability of BSE for site characterisation purposes, the variability of different geotechnical parameters with depth were compared with the corresponding BSE profile for the selected location.

Fig. 3 shows the comparison of the BSE with basic soil parameters, intact dry density (IDD) and moisture content (w) of the recovered samples. IDD was found to correlate reasonably well with the BSE profile – an increase in density generally corresponds to an increase in drilling energy. A similar observation can also be made while comparing the moisture content data with BSE, with lower w values generally associated with higher BSE, and vice versa.

Notably at ~ 37 m, a sharp increase in BSE is observed which is not reflected in the soil parameters. Closer scrutiny of the data indicates that the spike is caused by a surge in fluid pressure, which in turn leads the drilling operator to increase the bit weight significantly. This instance highlights the importance of plotting fluid pressure to separate the effects of drilling operations from the ground conditions.

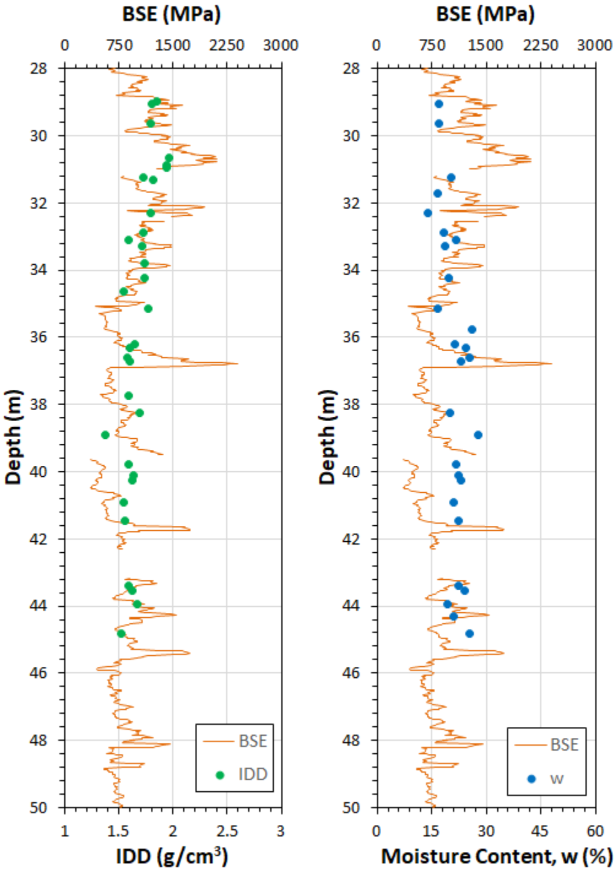

Figure 3. Comparison between BSE and basic parameters

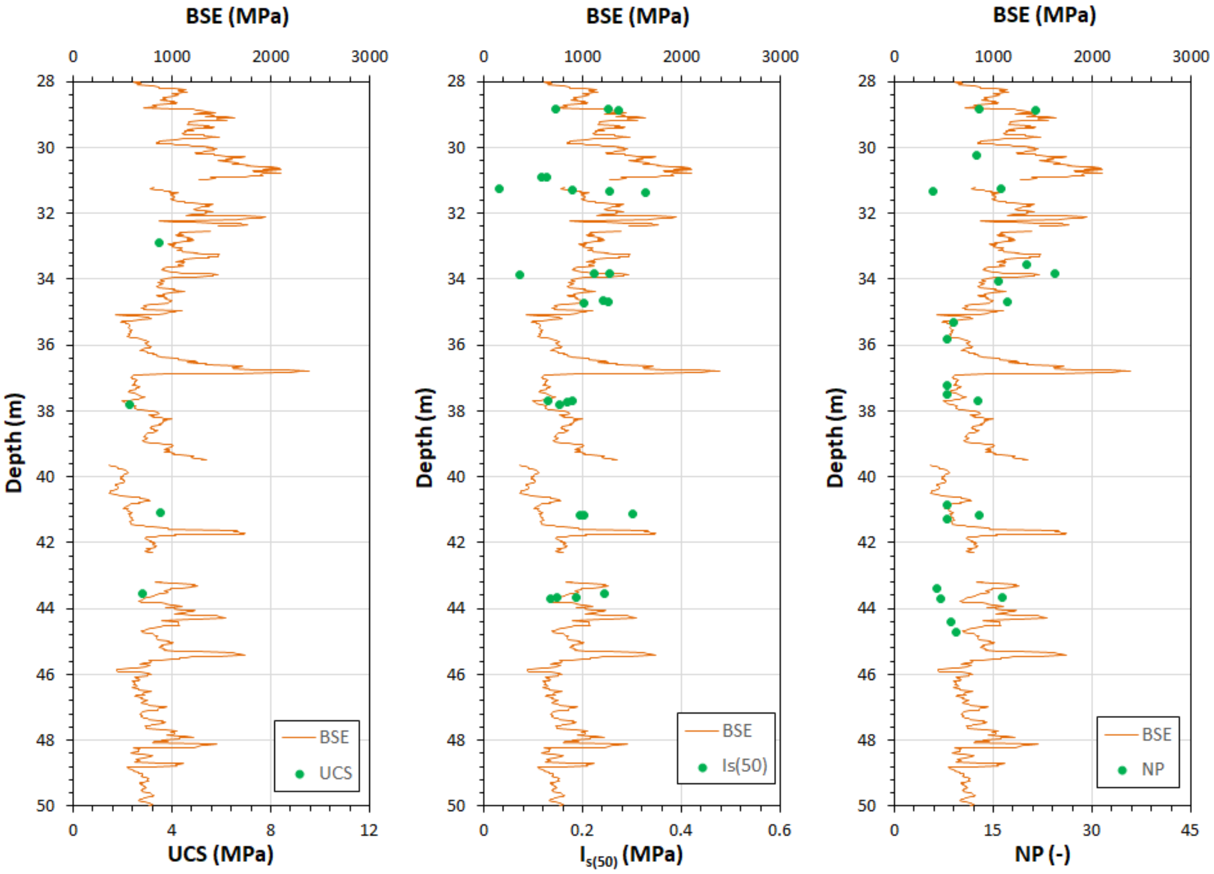

Figure 4. Comparison between BSE and UCS, $I_{s(50)}$ and NP strength parameters

Similar comparison between shear strength parameters such as unconfined compressive strength (UCS), point load index, $I_{S\ (50)}$ and needle penetrometer (NP) index are shown on Fig. 4. The results show that the BSE profile captures the variation in the strength values with depth reasonably well. It can also be noted that although the measured values of both the $I_{S(50)}$ and NP generally follow the BSE profile, there is some scatter in the data. This is expected as the point load and needle penetrometer tests are index tests and are generally carried out on smaller sections of the samples. Therefore, these tests are more likely to be affected by localized variability of the material.

Young's modulus and Poisson's ratio corresponding to 50% strength (i.e. E_{50} and ν_{50}) are commonly used as a deformation parameter for engineering design purpose. Fig.5 shows the measured values of E_{50} and ν_{50} along with the BSE profile at this borehole location. The BSE profile captures the variation in the deformation parameters with depth reasonably well, as higher E_{50} and lower ν_{50} values are generally observed for materials with higher BSE.

Overall, the results indicate the BSE profile generally captures the expected trend based on the laboratory test data. Therefore, the BSE profile may be used to develop generalised relationships that can be used to derive continuous soil profile with depth in a similar fashion to other in-situ tests such as CPT. This is further discussed in the following sections.

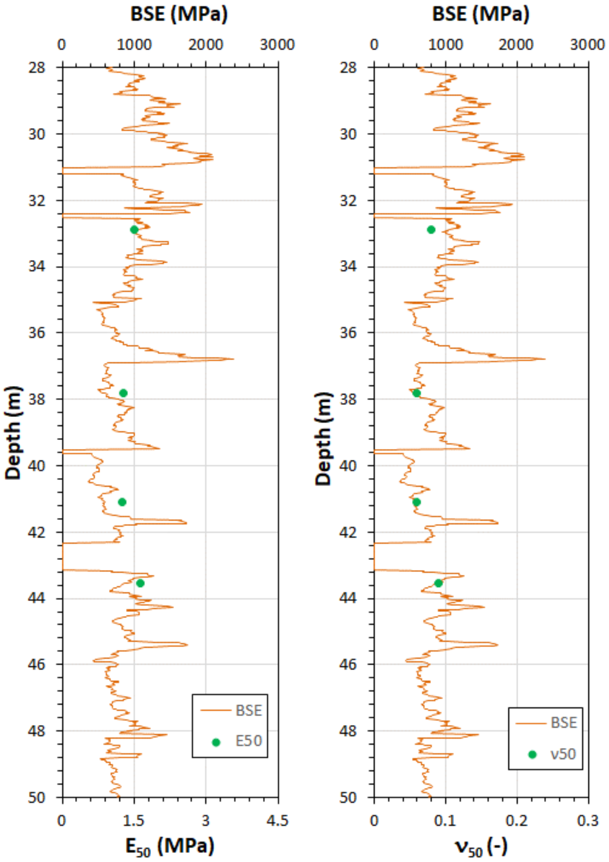

Figure 5. Comparison between BSE and deformation parameters

4. Generalised relationships

The exercise shown in Section 3 linking the laboratory test data with the BSE profile was limited to data from a single location with samples of similar material type. However, based on experience with CPT based correlations available in the literature, it can be expected that correlation/scaling factor between laboratory test data and BSE is not unique - instead it depends on several factors such as the material type, in-situ state of the sample, etc.

To develop generalised correlations between different geotechnical parameters and BSE, the results from different locations covering a wide range of material types and in-situ state of the samples were interpreted. This will allow test data from one location to be scaled across the project site. The generalised relationships developed for different engineering parameters considering the site-wide data from the studied windfarm are discussed in the following sections. Note that the results from more than 15 locations across the site with sample depths ranging from 8 m to 70 m were used.

For each of the generalised relationships discussed below, a low estimate (LE), best estimate (BE) and high estimate (HE) trendlines are also shown. These lines were derived based on visual observation and intended to represent approximately P_{10}, (i.e. 10% of data lie below the line), P_{50} (best fit of the data) and P_{90} (90% of the data lie above the line) of the overall test data.

4.1. Basic soil parameters

Basic soil parameters are used to define the in-situ state of the sample and typically include moisture content and density of the sample. Fig.6 and Fig. 7 show the variation in the intact dry density (IDD) and moisture content (w) of the tested samples as a function of BSE. The results show a reasonable trend between IDD, w, and BSE. In general, the results show increasing IDD with increasing BSE, while w is found to reduce with increasing BSE. This is consistent with the expected trend for cemented materials.

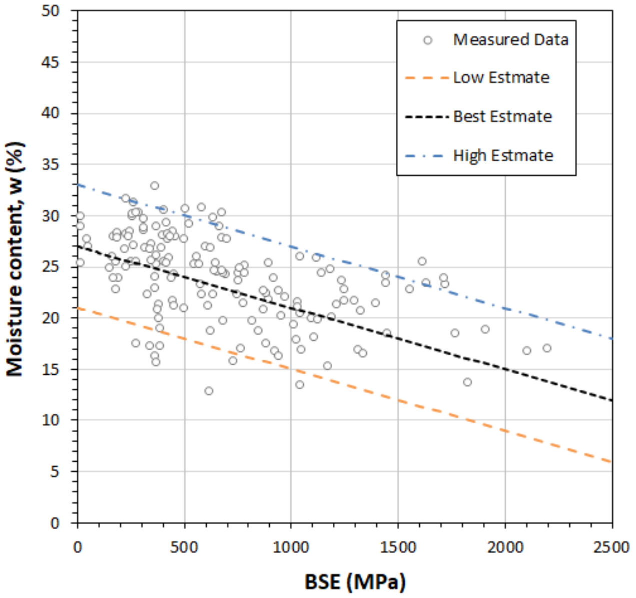

Figure 6. Relationship between IDD and BSE

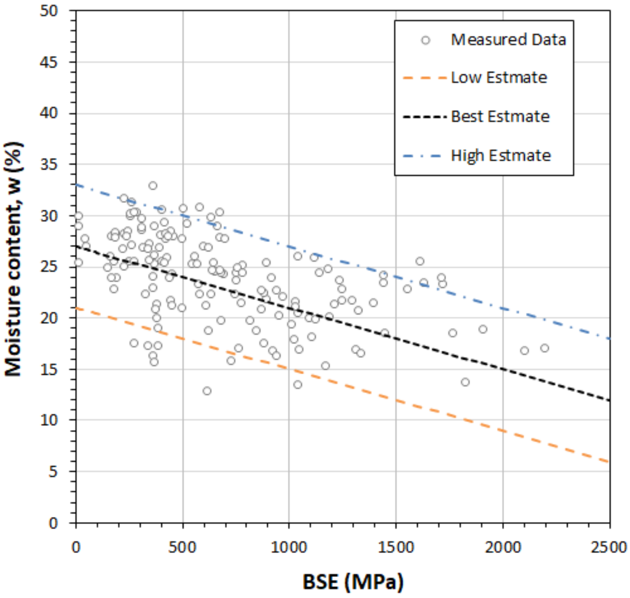

Figure 7. Relationship between w and BSE

4.2. Strength Parameters

The shear strength of cemented samples was assessed using unconfined compressive strength (UCS), point load (PL) and needle penetrometer (NP) tests. PL and NP tests were performed on smaller sample sections, generally unsuitable for standard UCS tests. However, unlike UCS, PL and NP tests do not provide direct measurements of the shear strength of the material. To estimate shear strength, the results obtained from PL and NP test are compared with the corresponding UCS tests performed on immediately adjacent samples. These results were used to establish relationships between UCS and point load index, $I_{s(50)}$ and between UCS and needle penetrometer ratio (NPR). Based on the site-specific data, the following relationship were used in this paper:

$$\text{UCS} = 16 \times I_{S(50)} \tag{2}$$

$$\text{UCS} = 0.28 \times \text{NPR} \tag{3}$$

In the following sections, the shear strength of cemented/rock samples obtained from different tests are discussed.

4.2.1. Correlation between UCS and BSE

The correlation between UCS and BSE was examined considering the ratio between BSE and UCS as follows:

$$N_{BSE} = \frac{\text{BSE}}{\text{UCS}} \tag{4}$$

This is similar to the cone factor (N_{kt}) approach commonly used to assess the shear strength based on CPT data (e.g. Lunne et al., 1997).

Fig. 8 presents the comparison between the UCS and BSE for the tests performed on samples from multiple borehole locations across this UK windfarm project site. Note that UCS value for PL and NP tests were estimated using the best estimate correlations discussed above. Although there is some scatter in the data, the overall trend and the range of data is consistent with similar relationship based on cone resistance for uncemented material (e.g. Sharma et al, 2024).

The LE and HE trendlines that capture the overall range of the data and BE trendline that represent the overall average of the data is also shown on Fig. 8. The proposed trendlines were developed such that they slightly biased towards the directly measured UCS values. These trendlines may be used in combination with the BSE profile to assess the shear strength of materials. This is further discussed in the following sections.

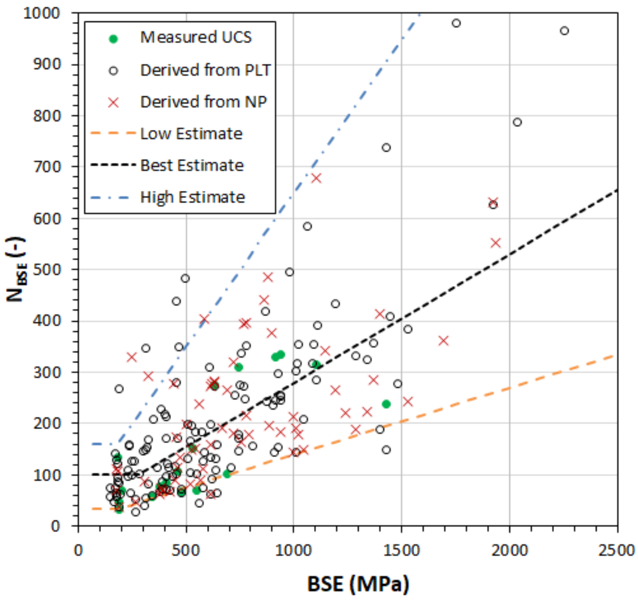

Figure 8. Relationship between UCS and BSE

4.3. Deformation Parameters

Fig.9 and Fig. 10 show the variation in the E_{50} and ν_{50} of the tested samples as a function of BSE. These values were estimated using the stress-strain curve obtained from the UCS tests. Although only a limited number of test data was available, the overall trend is consistent with expectation i.e. higher E_{50} and lower ν_{50} values are observed with increasing BSE.

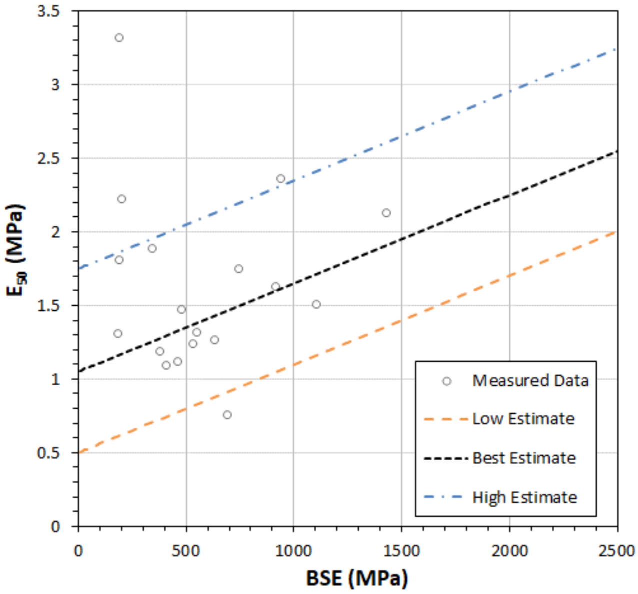

Figure 9. Relationship between E_{50} and BSE

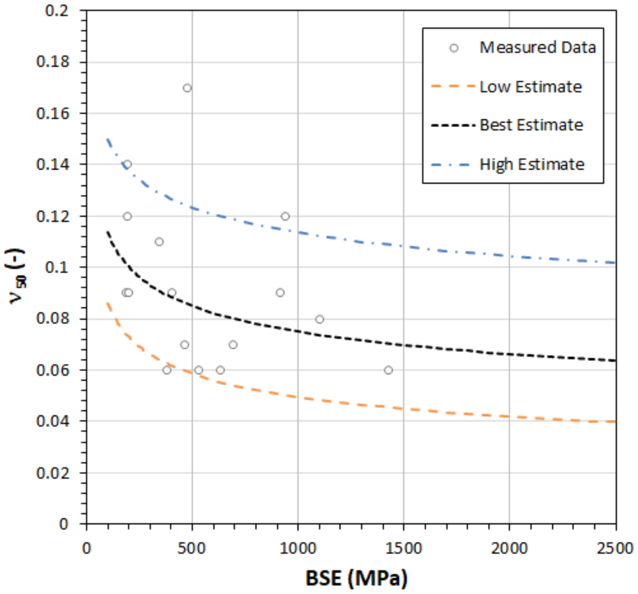

Figure 10. Relationship between ν_{50} and BSE

5. Derivation of design profiles – An example

The generalised relationships between different geotechnical parameters presented above may be used in combination with the site-specific BSE profile to develop design profiles required for engineering analysis.

Fig.11 shows an example of derived design profiles for IDD, UCS, E_{50} and ν_{50} based on the generalised relationships presented in Fig. 7, Fig. 8, Fig. 9, and Fig. 10 respectively, and the average BSE profile shown on Fig. 2. The laboratory test data obtained from the test performed on samples from corresponding boreholes are also shown on Fig. 11. It can be observed that not only do the proposed trendlines reasonably capture the laboratory test results, but additional information is provided at depths not covered by the discrete testing dataset. For example, based on the laboratory test data alone, it is not possible to capture the potential range of strength and deformation parameters, as indicated by the LE and HE profiles shown on Fig. 10. Also, it can be noted that, although the BE line fits the IDD data well, the small and discrete test data set provides an upper and lower bound to the drilling derived profile that matches the Chalk IDD range outlined by Mortimer (2004), where IDD values in the range of approximately 1.3 g/cm^3 corresponds to the lowest density chalks and > 2 g/cm^3 corresponds to the highest density chalks are reported.

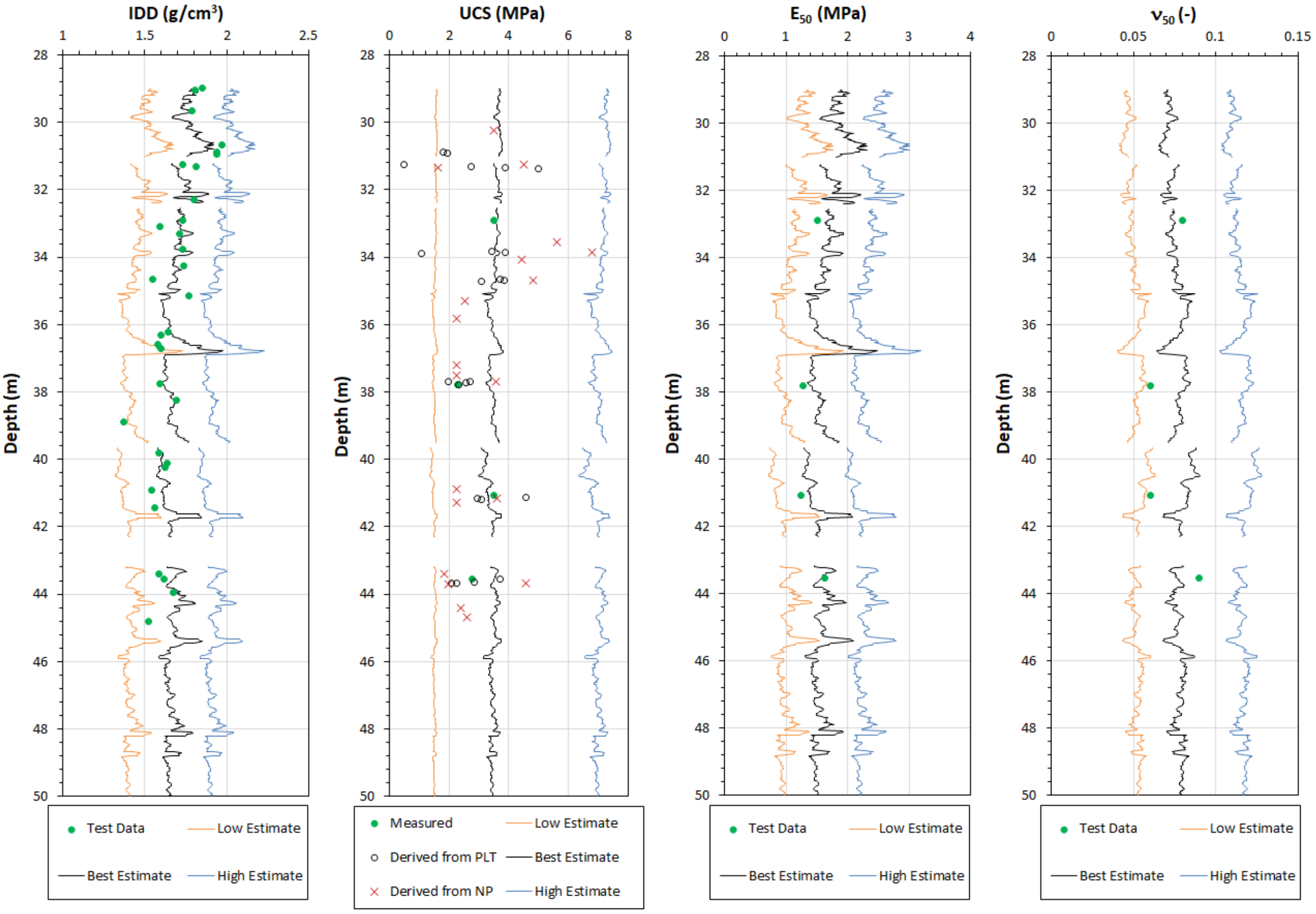

Figure 11. Example design profiles derived using generalised relationships and site-specific BSE profile.

6. Summary, conclusions, and recommendation

The following summary and conclusions can be drawn from the test results and interpretation of the data presented in this paper:

- Variably cemented materials are commonly encountered in shallow water locations and are an important part of the geotechnical site characterisation for offshore development projects. However, geotechnical characterisation of cemented materials is often challenging due to lack of data. The standard in-situ testing (e.g. CPT) and sampling (piston/push and rock coring) data is often limited due to refusal in hard layers or recovery of poor-quality samples.
- Borehole specific drilling parameters are routinely measured during geotechnical site investigation. However, these parameters are not generally used for geotechnical site characterisation purpose.
- This paper investigates the use of drilling data for site characterisation purposes on variably cemented materials.
- The drilling data was processed to derive the borehole specific energy using the relationship presented in Teale (1965). Comparison of the BSE profile with the borehole logs developed based on visual inspection of the sample, it was found that BSE not only provides continuous energy profiles with depth but also the BSE profile reasonably well captures the variability of the material types with depth.
- The variability of different geotechnical parameters with depth were compared with the corresponding BSE profile. The results indicate the BSE profile reasonably captures the observed trends based on the laboratory test data.
- Based on the results obtained from an offshore windfarm project, a generalised relationship between various geotechnical parameters and BSE are proposed in this paper. An example is also shown of how the generalised relationship based on BSE profile can be used to derive design profile for a selected location.

The paper shows that drilling data may be used for site characterisation purposes especially for sites with variably cemented materials where the standard testing and sampling methods provide limited data due to refusal in hard layers or recovery of limited poor-quality samples. It is important to note that drilling data is not an alternative to CPT and sampling. However, considering that recovery of drilling data does not require any additional effort, proper measurement, and processing of drilling data could be useful additional information for engineering purposes.

The data presented in this paper are specific to the rotary coring stage of the drilling. However, drilling data can also be measured at any stage during the drilling process (such as wash boring, casing etc. In addition, there may be scope to optimize the measurement of drilling data to get better quality data for geotechnical characterisation purposes (e.g. Chen et al 2016). This may need further investigation.

Furthermore, the effects of fluid pressure on the drilling operations was not considered when plotting BSE presented in this paper. It is possible that fluid pressure may affect the drilling parameters which may need further investigation/research.

It is also important to note that the drilling data and generalised relationship presented in this paper are specific to the studied project and its applicability for other projects needs to be verified using site-specific data.

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