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Soil classification of NGTS sand site (Øysand, Norway) based on CPTU, DMT and laboratory results

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ABSTRACT: The Norwegian GeoTest Site project (NGTS) established five research sites in Norway in 2016. The sites are referred to as sand, soft clay, quick clay, silt and permafrost. The project is funded by the Research Council of Norway and the aim of the project is to establish, characterize, share digital data and manage the use of the test sites in the coming 20 years. The sites are open to other researches for developing and calibrating new tools and techniques. The focus of this paper is the soil classification of the NGTS sand site at Øysand based on Cone Penetration Tests (CPTUs) and Dilatometer Tests (DMT). The fluvial and deltaic deposit at Øysand consists of a 20–25 m fine silty sand with occasionally high content of gravel. The deposit is generally normally consolidated in loose to medium dense states. The *in situ* test data is further supported by laboratory test results from a 20 m long and continuous borehole. This paper presents the results of two CPTUs and one DMT in addition to laboratory test results, all from the same location at the research site. The prediction of *soil behavior type* and unit weights from CPTU and DMT tests, based on existing correlations, are compared qualitatively to the soil classification from grain size distribution and unit weights from laboratory measurements.

1 INTRODUCTION

1.1 *Background*

Loose sandy soils are challenging materials in geotechnical engineering with many difficulties associated with sampling undisturbed material and interpretation of *in situ* and laboratory test data. To this aim, the Norwegian Geotechnical Institute (NGI) and its partners, the Norwegian University of Science and Technology (NTNU), SINTEF Building and Infrastructure, the University Centre in Svalbard (UNIS), and the Norwegian Public Roads Administration (NPRA) recently established a research site on a natural sand deposit at Øysand, Norway. This site is part of a larger research project called the Norwegian GeoTest Site (NGTS), funded by The Research Council of Norway (L'Heureux et al. 2016, 2017).

1.2 *Site location*

The Øysand research site is located in central Norway, approximately 15 km south of Trondheim (Figure 1). The area available for geotechnical investigations at Øysand is about 35,000 m^2 and is used only for agricultural purposes. The deposit at the site consists of fluvial material, underlain by deltaic material deposited at the mouth of the Gaula River. Today the Gaula River borders the site to the east.

1.3 *Aim of the study*

The purpose of this study is to present preliminary results summarizing the geotechnical properties of the Øysand research site. Focus is given to the interpretation of soil type and unit weight based on piezocone (CPTU) and dilatometer (DMT) tests. The results are compared qualitatively to the grain size distributions (GSD) and unit weights measured in the laboratory. The results will form a useful reference to engineers working on similar intermediate soils worldwide and will be used as reference for further research planned at this site.

2 DATA AND METHODS

2.1 *Field data and methods*

Field tests including state of the art techniques for field characterization e.g. seismic CPT and DMT, multichannel analysis of surface waves, MASW, symmetrical resistivity profiling, SRP, Multi-sensor core logging, MSCL, electrical resistivity tomography, ERT, ground penetrating radar, GPR, etc. were carried out in 2016 and 2017. However, this paper only presents the CPTU and DMT results from locations nearby borehole OYSB09, as illustrated in Figure 1.

NGI retrieved disturbed samples at borehole OYSB09 using a 54 mm GEONOR piston sampler. Continuous sampling was carried out to

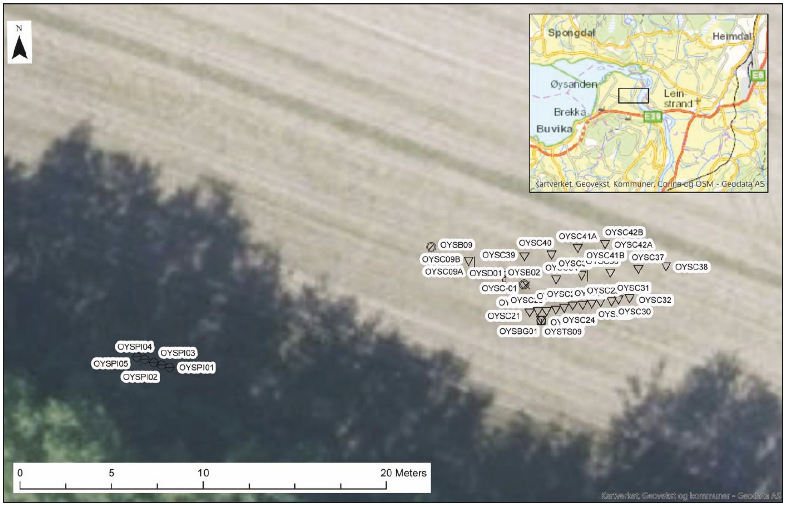

Figure 1. Location of soil investigations.

20 m below ground level except in the depth range between 4 to 5 m, where a hard layer of gravelly material was drilled through.

CPTU tests were performed to 20 m depth using standard 10 cm^2 Geotech cones at the locations identified as OYSC02 and OYSC09. The CPTUs had area ratios of 0.857 and 0.844 respectively. CPTUs where performed following ISO 22476-1:2012. The tests included predrilling to a depth of 1 m and 2 m respectively to avoid damaging the cone while penetrating trough the top gravelly layer. Moreover, predrilling was also needed during the CPTU test at OYSC09 between ca. 4 m and 6 m depth because of a gravelly layer, which could have damaged the cone. The total depth of the CPTU tests was 20 m.

The same DMT test setup as described by TC16 (2001) and Marchetti (1980) was used at Øysand, while ASTM D6635–01 (2007) testing procedures were followed. Two days of testing were required (Oct. 27th and Nov. 2nd, 2016) for the DMTs, because of the need to predrill through the gravel layer between 3.5 m and 6.0 m depth. The total achieved depth of the DMT test was 18 m.

2.2 *Laboratory data and methods*

NGI's main laboratory in Oslo, Norway, carried out index testing to establish the water content, W, unit weight, UW, and grain size distributions, GSD, of the 54 mm diameter samples from borehole OYSB09. This borehole was located at about 5 m from the CPTs and DMT locations. Table 1 provides an overview of the number of tests carried out and testing procedures followed. As seen in this table, a representative amount of tests has been performed.

Table 1. Summary of relevant laboratory tests.

Type of test	No. of tests	Reference
W	19	NS 8013
UW	36	NS 8011
GSD	20	NS 8005

Samples that contained mainly sand and gravel were subjected to dry sieve analysis, while materials containing more than 5% silt and clay particles were wet sieved on a 75 mm sieve before dry sieving as per the standard mentioned in Table 1. The falling drop method described in Moum (1965) was used for samples containing mainly silt or clay.

3 GENERAL STRATIGRAPHY AND IN-SITU CONDITIONS

3.1 *Stratigraphy*

The overall stratigraphy at the site represents a general coarsening upward sequence as typically observed in deltaic sequences. A snap of the site stratigraphy, using field and lab data is shown in Figure 2. Two main soil units are identified down to 20 m below the ground surface. Unit 1 at the top is up to ca. 10 m thick and consists of a fine to coarse sand with presence of gravel. Unit 2 consists of finer material comprising medium silty sand and sandy silt with traces of organic material.

3.2 *Groundwater level and pore pressures*

Piezometers were installed at several depths intervals down to 20 m below the surface near borehole

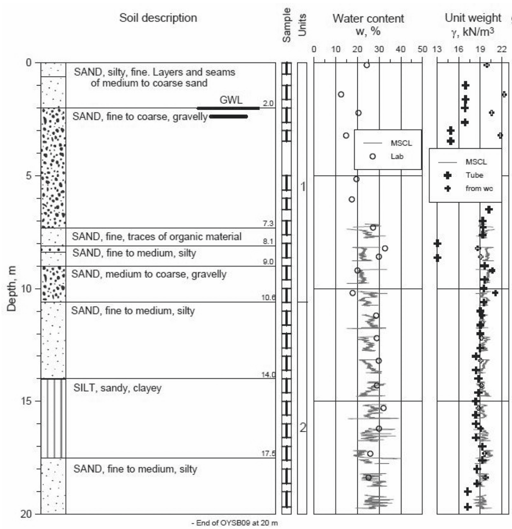

Figure 2. Borehole log OYSB09.

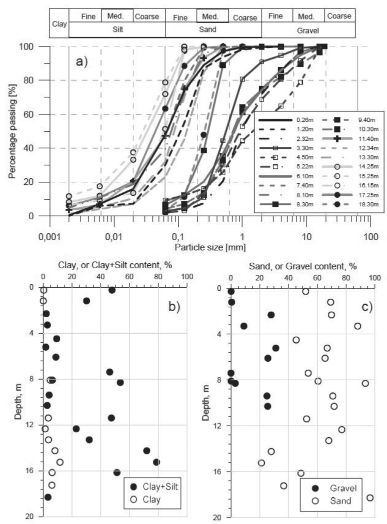

Figure 3. Grain size distribution from borehole OYSB09.

OYSB09 in 2017. The results show mostly constant values in time with hydrostatic pore pressure from 2 m below ground level where the groundwater level is found.

4 LABORATORY TEST RESULTS

GSD curves of samples from borehole OYSB09 are shown in Figure 3a. Figures 3b and 3c show the fines and coarse contents per depth respectively. The GSDs results form the basis of the soil description in the borehole log presented in Figure 2. From this figure, it can be inferred that gravel to silt can be found at Øysand. The predominant soil being silty sand.

Figure 2 shows also values of UW calculated based on W, derived from Magnetic Susceptibility Core Logging (MSCL) readings and estimated using the sampled 54 mm piston tubes. Note that the estimated UW from piston samples is expected to be less reliable in the gravel soil, because during the sampling process dense soil may be loosened and heavily disturbed. Good agreement between all measurements of UW by the three presented methods is found below 5 m depth, where the representative value is 19 kN/m^3. Above 5 m depth, UW from WC is consistently higher than the obtained from the piston samples. However, the representative value of UW was used when interpreting DMT and CPTU readings.

5 IN SITU TEST RESULTS

CPTs have been available to geotechnical engineers since the 1930s as a mechanical test. The incorporation of electric strain-gauged load cells was introduced in the 1960s. A recent ISO standard (ISO 22476-1:2012) covers equipment, procedures and reporting which has been applied for soil investigations at Øysand. Lunne et al. (1997) presented methods for interpretation, which are used herein.

Figure 4 shows the CPTU results including cone resistance, q_c, unit sleeve friction resistance, f_s, and the pore pressure measured behind the cone, u_2. Figure 5 illustrates the DMT results from sounding OYSD01 close to borehole OYSB09 where I_D is the material index, K_D is the horizontal stress index and E_D is the dilatometer modulus as defined in TC 16 (2001). These parameters can be regarded as intermediate parameters calculated from the corrected first and second DMT readings, p_0 and p_1, as follows:

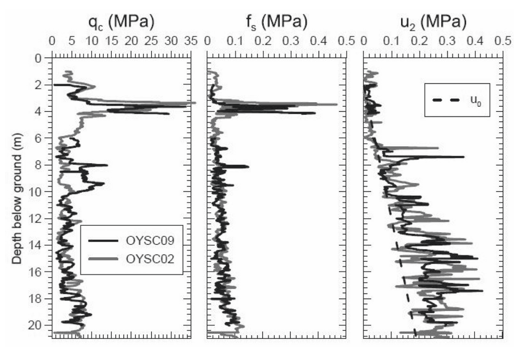

Figure 4. CPTU results OYSC02 and OYSC09.

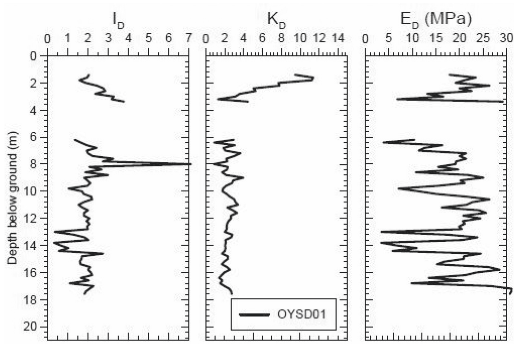

Figure 5. DMT results OYSD01.

$$I_D = (p_1 - p_0)/(p_0 - u_0) \quad (1)$$

$$K_D = (p_0 - u_0)/\sigma'_{v0} \quad (2)$$

$$E_D = 34.7(p_1 - p_0) \quad (3)$$

Here u_0 is the pre-insertion pore pressure and σ'_{v0} is the pre-insertion effective overburden stress calculated assuming a total unit weight of 19 kN/m^3.

It is worth mentioning that three independent measurements (q_c, f_s, u_2) are obtained from a CPTU test, while only two (A and B reading) are obtained from a DMT test (excluding penetration resistance record and C-readings). In addition, the CPT provides close to continuous data while the DMT provides data every 20 cm.

6 SOIL CLASSIFICATION & UNIT WEIGHT

6.1 *Soil classification and unit weight from CPT and DMT results*

Based on the work of Wroth (1984), Robertson (1990) suggested the following normalized CPTU parameters to identify soil behavior types:

$$Q_{tn} = (q_t - \sigma_{v0})/\sigma'_{v0} \quad (4)$$

$$F_r = f_s/(q_t - \sigma_{v0}) \quad (5)$$

$$B_q = (u_2 - u_0)/(q_t - \sigma_{v0}) \quad (6)$$

where: q_t is the corrected cone resistance and σ_{v0} and σ'_{v0} are the pre-insertion *in situ* total and effective vertical stress respectively.

Robertson (1990) suggested two charts based on the combination of either Q_{tn} & F_r or Q_{tn} & B_q, but recommended that the $Q_{tn} - F_r$ chart was generally more reliable.

Jefferies & Davies (1993) identified that a soil behavior type index, I_c, could approximate the material boundaries in the $Q_{tn} - F_r$ chart where I_c is simply the radius of concentric circles. According to Robertson & Wride (1998), the circles can be described using the following equation:

$$I_c = [(\log F_r + 1.22)^2 + (\log Q_{tn} - 3.47)^2]^{0.5} \quad (7)$$

CPTU and DMT tests are mechanical in nature and both Robertson (1990) and Marchetti (1980) suggested the soil classification based on these tests indicates the *soil behavior type (SBT),* and not a strict soil classification like that obtained from GSD. Comparison should therefore be qualitative, rather than quantitative. Moreover, the classification from CPTU and DMT are generally empirical and care should be exercised when a dataset is outside the domain of the data from which the empirical method was developed, like for the gravelly sand layers at Øysand.

Robertson (1990) observed that most uncemented, normally consolidated, young soils tend to follow an approximately diagonal line between the upper left corner and the lower right corner in the Q_{tn}-F_r chart. Figure 6 shows how the results from Øysand display the same property except for the more overconsolidated sand towards the top of the stratigraphy.

Similarly, Marchetti (1980) noted that in normally consolidated cohesive soils where the soil has not been influenced by aging, structure or cementation, the value of K_D is approximately 2. As seen in Figure 5, K_D from DMT test at Øysand approaches the value of 2 below 6 m depth, which is consistent with the CPTU results and geological history of the site.

From Figure 6, it is also observed that the deposit falls mainly into zones 4 to 6, hence described as silt mixtures to sands. The estimated UW, normalized by the unit weight of water, γw,

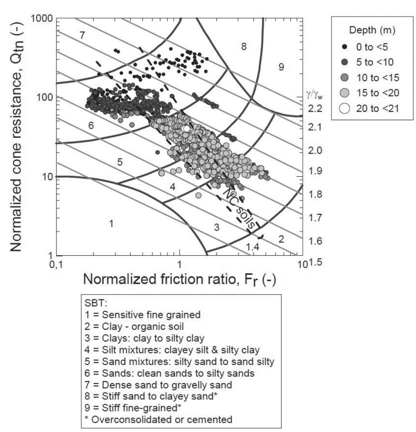

Figure 6. SBT after Robertson (1990) for OYSC02 & OYSC09.

are generally in the range of 1.7–1.9. This is on the low side of the results from laboratory testing shown in Figure 2. The estimation of UW based on CPT, shows significant scatter (see Fig. 6), especially towards the top of the stratigraphy, where no obvious trend seems to exist. The assumption of a single UW is certainly not possible from the CPTU interpretation, and hence in disagreement with the general trend of laboratory and MSCL results (Figure 2).

Marchetti & Crapps (1981) proposed a log-log chart, based on I_D and $E_{D,}$ for estimating the soil type and UW. E_D distinguishes mud/peat from other soil types and relates to the material unit weight as presented in Figure 7. The material index differentiates between clays, silts and sand soil types. Figure 7 shows the interpreted DMT results from Øysand. As seen in this figure, sandy silt or silty sand, in terms of their behavior, are identified. The occasionally high content of gravel is not indicated. The results propose a material unit weight mainly in the range of 18 to 19 kN/m^3, which is in good agreement with the general trend from laboratory and MSCL.

Table 2 summarizes the boundaries for the SBT indices in the CPTU and DMT frameworks proposed by Robertson (1990) and Marchetti & Crapps (1981). This table gives a better overview of the expected values of both I_C and I_D for identification of the soil behavior type.

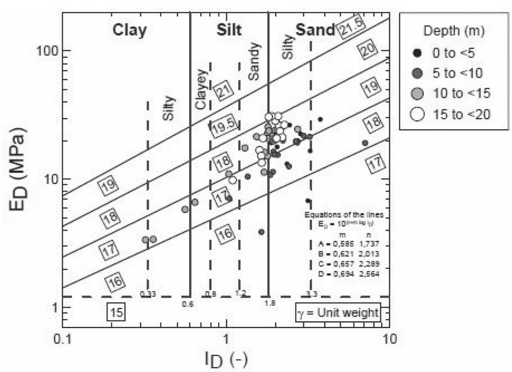

Figure 7. DMT-SBT chart after Marchetti & Crapps (1981) for DMT test OYSD01.

Table 2. Soil behavior type boundaries for I_C (CPT) & I_D (DMT).

Soil behavior type	I_C (CPT)	I_D (DMT)
Clay	Ic > 2.95	$0.1 < I_D < 0.6$
Silt	$2.05 < I_C < 2.95$	$0.6 < I_D < 1.8$
Sand	$I_C < 2.05$	$1.8 < I_D < 10.0$

6.2 *Comparison of soil classification and unit weight from CPT and DMT with laboratory results*

To compare the classification from DMT and CPTU as function of depth, a simple linear transformation of the DMT material index has been made. The equation is given below:

$$I_D^* = 0.75 I_D + 1.6 \quad (8)$$

where: I_D^* has the same soil behavior boundary values between clay and silt and silt and sand as the CPTU material index I_c. The uniqueness of the criteria, proposed by Marchetti (1980), is preserved.

Figure 8 displays the transformed DMT material index from OYSD01 and the CPTU index from OYSC02 and OYSC09 with depth. It can be seen that both the DMT and CPTU predict well the overall SBT at Øysand although the high contents of gravel are not identified. At greater depths both the DMT and CPTU reflects the change in soil behavior from highly drained to more undrained to some degree.

The trend of higher content of silt and clay particles around 14 m depth is also evident from the laboratory tests. It is further noted that the DMT seems to identify the material as generally coarser than the CPTU.

The two CPTUs show consistency in the interpretation of soil behavior type. At 9 meters depth, the two CPTUs show a difference in the SBT which

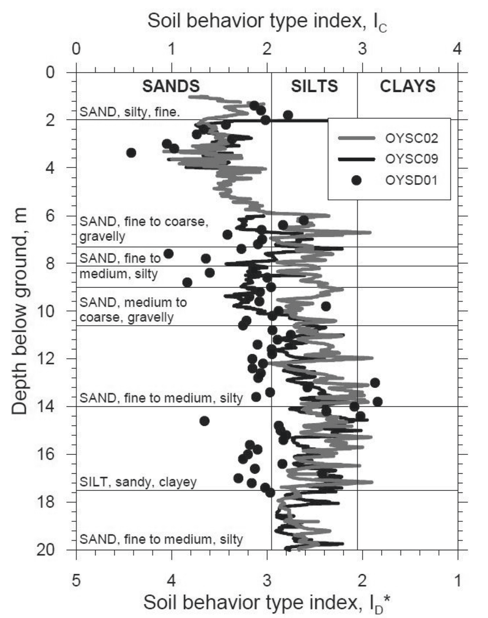

Figure 8. SBT-indices with depth for OYSB09.

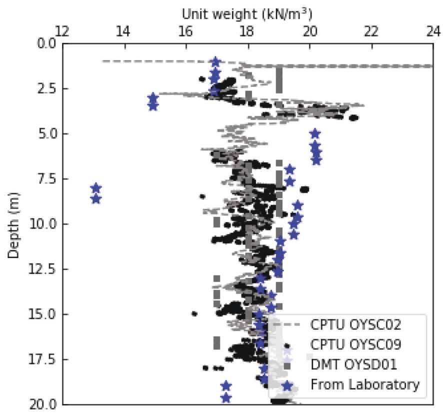

Figure 9. Unit weight from CPT (Robertson, 1990), DMT (Marchetti & Crapps, 1981) and 54 mm tube samples.

is thought to be due to lateral variability in the soil conditions of the site.

It can also be seen that the soil behavior type index, I_C, does not predict as much clay behavior as the Q_{tn}-F_r chart. This is due to the definition of I_C, which is not able to match the soil behavior chart exactly. For Øysand, the CPTU soil behavior index seems to give a more correct picture of the soil conditions than the soil behavior chart.

Figure 9 illustrates the unit weight from in situ tests and laboratory measurements with depth. It can be seen that the values from CPTs are generally lower than the unit weights from laboratory measurements on 54 mm tube samples between 5 and 15 m depth. DMT results show similar tendency between 5 and 15 m depth while it displays higher unit weight at shallow depth compared to the 54 mm tube.

7 CONCLUSION

The Norwegian GeoTest Site project (NGTS) established five research sites in Norway in 2016. These are referred to as sand, soft clay, quick clay, silt and permafrost sites. This paper presents laboratory and *in situ* test results (CPT, DMT and MSCL) for the sand site with focus on soil classification.

Soil classification based on grain size distribution, CPTU (Robertson 1990) and DMT (Marchetti & Crapps 1981) have been presented and compared qualitatively. The CPTU and DMT results support the assumption that the site is a close to normally consolidated loose sand deposit. The interpretation of the in situ results show that the soil behavior type is generally sandy silt or silty sand, which is consistent with the laboratory results. In situ tests failed to identify the occasional high content of gravel, but the correlations are able to reflect the change from highly drained to more undrained material to some degree. This demonstrates how the existing correlations can be used to estimate soil behavior type with confidence for this site.

Existing correlations made it possible to compare the interpreted total unit weights from CPTU and DMT with values measured in the laboratory. The results from the DMT test matched the laboratory test results slightly better than the CPTU. Both DMT and CPTU predictions generally fall on the low side of the measured values from the laboratory. Some further refinement in the correlations may be necessary to better predict the unit weight from CPTU and DMT test results.

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