

Characterisation of Halden silt

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ABSTRACT: NGI recently established a research site on a natural silt deposit to accommodate some of the challenges related to intermediate soils. This study briefly summarises the geological history and the preliminary geotechnical characteristics of the Halden silt deposit. The stratigraphy at the site consists of four main units. Two structureless silt units sit between a 4.5 m thick layer of sand and a 6 m thick deposit of clay. Soil behaviour type charts classify the silt deposit as transitional soils/silts to low I_p clays. Classification tests indicate that these soils are low plasticity silts with very similar mineralogical content. The results presented will form a useful reference to engineers working on similar intermediate soils worldwide.

1 INTRODUCTION

Intermediate silty soils are still considered challenging materials in geotechnical engineering, and limited information on the engineering properties and how these relate to the geological background is available. This is primarily due to uncertainty in material behaviour, difficulties associated with sampling undisturbed material and the interpretation of *in situ* and laboratory test data. There is a need to provide guidance to practicing geotechnical engineers regarding characterization of silty material. To this aim, the Norwegian Geotechnical Institute (NGI) recently established a research site on a natural silt deposit.

The Halden Research Site is located in southeastern Norway, approximately 120 km south of Oslo (Fig. 1). Here the marine silt deposit is up to 10 m thick and uniform in nature. Over the last two years a series of geophysical, geological and geotechnical investigations have been carried out in the field and in the laboratory to characterize the natural silt deposit. This information will provide a basis for understanding the main factors controlling the engineering properties.

The purpose of this study is to present preliminary results summarizing the geological history and the geotechnical characteristics of the silt deposit at the Halden Research Site. The results presented will form a useful reference to engineers working on similar intermediate soils worldwide. Due to restrictions on the length of this study, we focus on the most significant properties.

2 GEOLOGICAL SETTING

The Halden Research Site is a recreational park area surrounded by hills, minor ravines and landslide scars. The site elevation is about 29 m above sea level and it slopes gently to the SW/W. Deposits at the site consists of marine and fjord marine sediments that emerged from the sea following a fall in relative sea level in the Oslofjord region during the last c. 11 000 years. During the post-glacial period, the depositional environment mainly led to hemipelagic deposition in a fjord marine environment. Due to the steady isostatic uplift in the Holocene and the fact that the sediments deposited continuously during a single period of submergence (Kenney, 1964), the soils in the study area are expected to be essentially normally consolidated except for some surface weathering, desiccation or in the vicinity of slide scars.

3 FIELD AND LABORATORY METHODS

3.1 *Field tests*

Several investigation methods are combined to provide information on the natural silt deposit and facilitate the understanding of the geotechnical behaviour and its link to the geological history. At present, geotechnical site investigation methods include Electrical Resistivity Tomography (ERT), several Total Pressure Soundings (TPS), Cone Penetration Tests with pore pressure measurements (CPTU), Seismic



Figure 1. Location of Halden Research Site.

Cone Penetration Testing (SCPT), Resistivity Cone Penetration Testing (RCPT), dissipation tests (Paniagua et al. 2016) and soil sampling. The latter was performed using two different Geonor thin walled stationary piston samplers; the K-100 54 mm composite sampler with zero inside clearance ratio (ICR) and a 10° cutting edge and the K-200 sampler modified to 72 mm inside diameter, ICR = 0 and a 5° cutting edge.

3.2 Laboratory tests

The samples were sent to the NGI and Geological Survey of Norway (NGU) laboratories in Oslo and Trondheim, respectively, for soil identification, classification, and assessment of index properties and advanced testing. Laboratory tests include; (i) Grain size distribution analyses by wet sieving (NSF, 1990), falling drop method (Moum, 1965) and hydrometer method (BSI, 1990); (ii) water content and Atterberg limits; (iii) unit weight of solid particles; (iv) mineralogical analyses using X-ray diffraction (XRD) and Scanning Electron Microscopy (SEM); (v) CAUC triaxial tests and (vi) constant rate of strain oedometer tests (CRS); (vii) geological and sedimentological analysis of the sediment using X-ray imaging and Multi-Sensor Core Logging techniques (magnetic susceptibility and gamma density) on 54 mm whole core samples. Whole core Gamma density (i.e. wet bulk density) and magnetic susceptibility (MS) were measured using the GEOTEK Standard Multi-Sensor Core Logger (MSCL-S) at 0.5 cm resolution with 5 s exposure/measurement time, see Figure 2. Total carbon (TC) and total organic carbon (TOC) measurements were performed on 7 samples.

4 SOIL CHARACTERISATION

4.1 Stratigraphy

The stratigraphy at the site is divided into four main units based on laboratory and *in situ* testing results, see Figure 2. It consists of c. 4.5 m of silty sand (Unit I) above c. 11 m of silt (Units IIA, IIB and III) and the final clay unit (Unit IV). Groundwater level was measured from an *in situ* stand pipe to be 2.5 m below ground level.

X-ray analyses show that both the Units II and III are structureless to mottled. Bioturbation has likely destroyed most of the primary sedimentary features. Such structureless sediments are common in fjord-marine environments subjected to hemipelagic sedimentation and seafloor biological activity (Hansen et al. 2010). In contrast, the Unit IV shows some weak laminations and the occasional presence of drop stones (sand/gravel particles) interpreted as ice rafted debris (IRD).

4.2 Water content and Atterberg limits

Natural water content (w) in Unit II generally falls between 28% and 31%. In Unit III the water content decreases with depth from about 27% at 12 m depth to about 21% at 15 m with an average value of 24%. The liquid limit (w_L) in Unit II varies between 31% and 37%, while in Unit III w_L is about 28%. Plastic limit (w_p) values are between 22% and 25% in the upper 11 m while below $w_p = 20\% - 22\%$. This gives plasticity indices (I_p) between 8% - 13% for Unit II. The average I_p is 10% between 4.5 m and 10.5 m. The plasticity data for Units I and IIA fall on and below the A-line while Unit IIB and III data points are on and above the A-line, respectively (see Fig. 3). The average I_p of Unit I and III (12 – 13 m depth) is 7.5% and 8%, respectively. Based on the data in Figure 3 the Unified Soil Classification System (USCS) classifies the soils as silty clay with sand to lean clay with sand.

4.3 Total unit weight and magnetic susceptibility

The total unit weight (γ_t), both estimated from whole core gamma density measurements and that based on water content, are presented in Figure 2. Total unit weight in Unit II generally falls between 18.9 kN/m^3 and 19.2 kN/m^3 . In Unit III the total unit weight increases with depth from about 19.5 kN/m^3 at 12 m to about 20.5 kN/m^3 at 15 m, with an average value of 19.9 kN/m^3 .

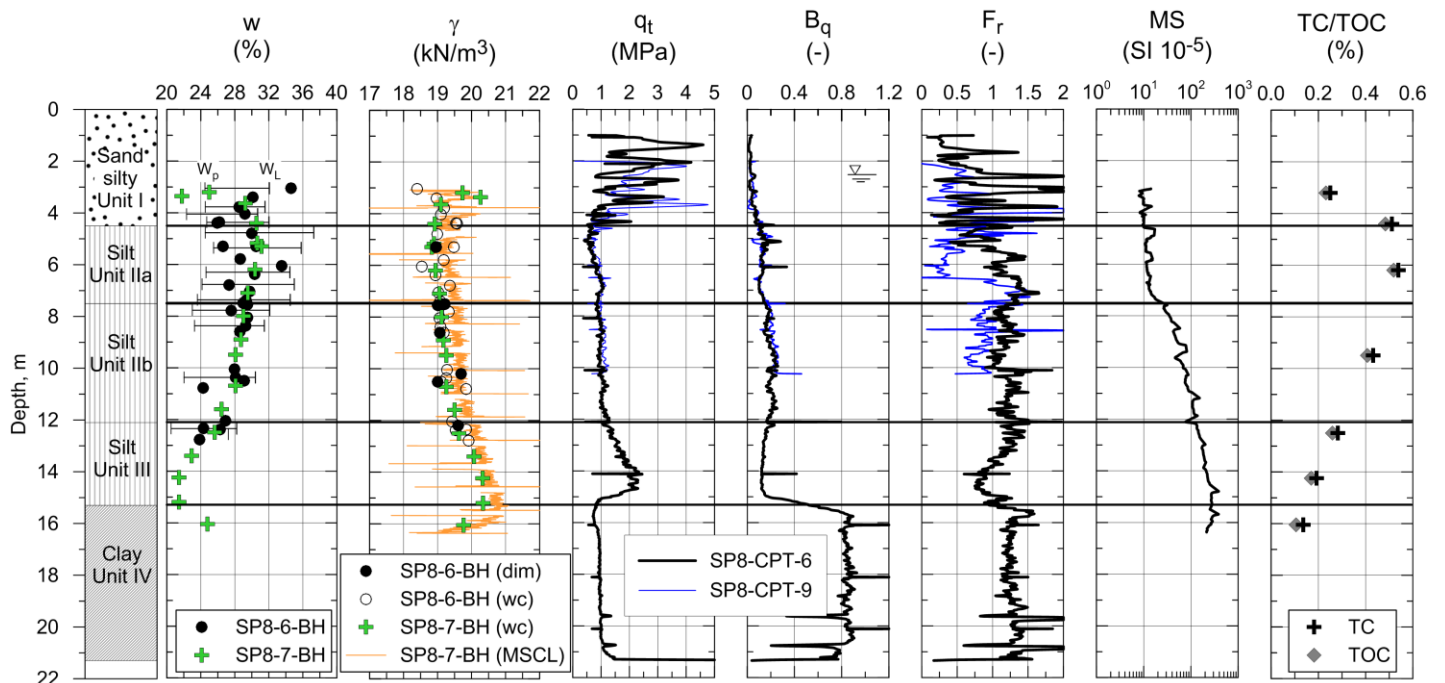


Figure 2. Basic parameters for Halden Research Site, corrected cone resistance, q_t , normalised pore pressure, B_q , normalised friction, F_r , versus depth from CPTU, magnetic susceptibility from MSCL, and TC/TOC. Whole core Gamma density (i.e. wet bulk density) is shown in yellow on the total unit weight log.

Results from MSCL-S show an increase in wet bulk density (or total unit weight) in Unit II. The trend is similar to that obtained from laboratory results based on direct measurements and from water content. However, the wet bulk density values from the MSCL-S are slightly higher than those from direct measurement or values based on water content analysis (Fig. 2). This may be due to whole core measurements where wet bulk density measurements integrate the entire sample thickness. The MS results show constant values in the first c. 2 m of Unit II and thereafter a linear increase with depth until culminating at the upper boundary of Unit IV.

4.4 Grain size distribution

Error! Reference source not found.4 presents typical grain size distributions for the silt in Units II and III. All results are from the falling drop method (Moum, 1963). However, there is a trend of lower clay content based on the hydrometer method and the clay content determined by this method varies between 4% and 8% in Units II and III.

4.5 Carbon content and mineralogy

In Unit II the average Total Carbon (TC) was measured to 0.486% with a range from 0.432% - 0.539%. In Unit III the average TC is 0.238%, ranging from 0.193% - 0.282%. Meanwhile the Total Organic Carbon (TOC) in Unit II average is 0.464% while the average is lower in Unit III at a value of 0.215%.

Table 1 presents the result of XRD analyses performed on soil from Unit II and III. They reveal very similar mineralogical content for the silt Units II and

III. Both units contain similar amounts of quartz, plagioclase, mica (muscovite and possibly illite), chlorite and amphibole. A Scanning Electron Microscope (SEM) image of a specimen from 6.4 m depth is presented in Figure 5.

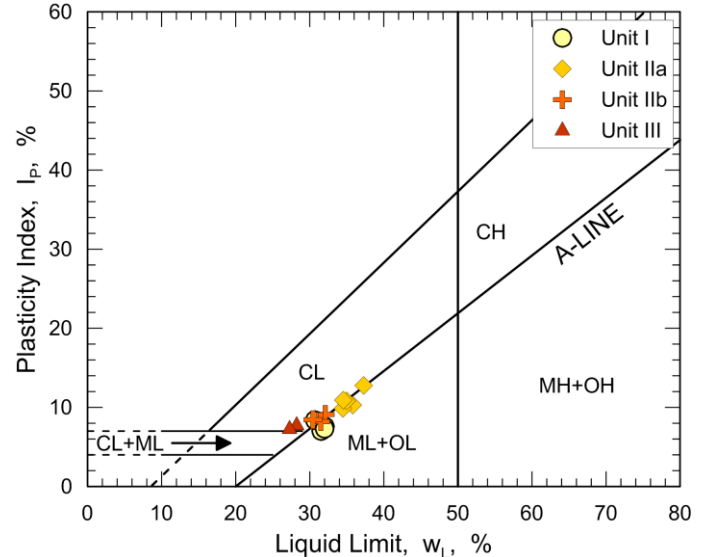


Figure 3. Plasticity chart, Unit I to III.

Table 1. Results from XRD analyses on silt Units IIa and IIb.

Depth (Unit)	Q*	K-F*	P*	M/I*	C*	A*	P*
m	%	%	%	%	%	%	%
6.2 (Unit IIa)	41	12	30	8	3	6	trace
9.5 (Unit IIb)	40	13	29	8	4	6	trace
13.4 (Unit III)	44	12	30	7	2	5	trace

* Q – Quartz, K-F – Potassium Feldspar, P – Plagioclase, M/I – Muscovite/Illite, A – Amphibole, P – Pyrite

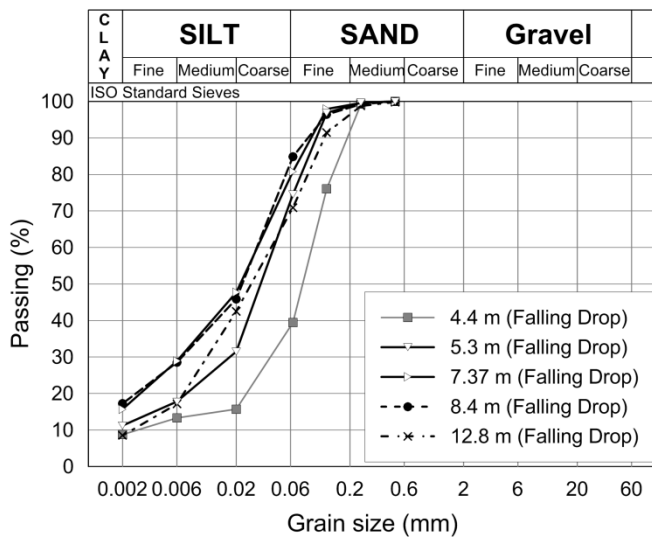


Figure 4. Typical grain size distribution curves, Unit II and III.

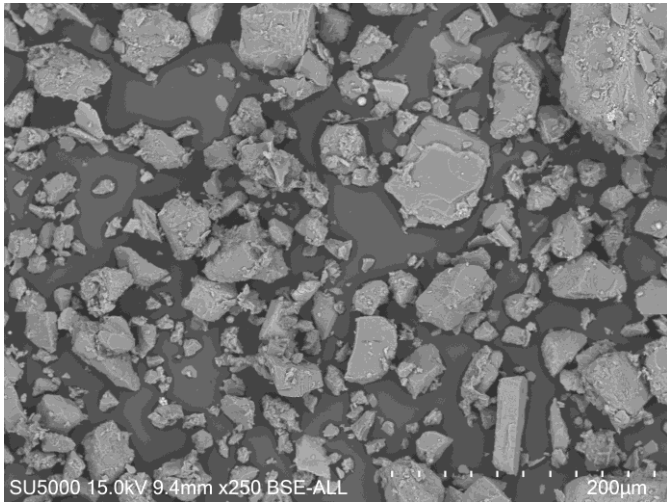


Figure 5. SEM image of a silt specimen from 6.4 m depth.

5 CONE PENETRATION TESTING

5.1 Corrected cone resistance and pore pressure

The corrected cone resistance (q_t) from CPTU tests, SP8-CPT-6 and SP8-CPT-9, are presented in Figure 2. The higher cone resistance in Unit I compared to the other units reflects the silty sand extending to about 4.5 m depth. Unit II has a uniform cone resistance throughout with q_t in the order of 1.0 MPa. In Unit III q_t increases from 1 MPa to 2.0 MPa between 12 m to 14.5 m before reducing to 1.0 MPa in the clay Unit IV. Pore pressure, u_2 , is not presented but increases steadily with depth to approximately 380 kPa at 14 m depth. There is a clear change in rate of increase in u_2 from 15 m to 17 m which coincides with the upper boundary of Unit IV. Below 17 m u_2 increases steadily with depth.

5.2 Soil behaviour type and soil classification charts

Figure 6 presents the traditional SBT chart from Robertson (1990) combined with the more recent classification chart from Schneider et al. (2008).

This system is based on Q_t and B_q and using Schneider et al. (2008) lines. Depth bias is known to occur when using soil classification charts if q_{net} and Δu_2 are not normalised, especially for sites with changes in OCR with depth. In this case only normalised charts are used for analysis. Unit I is classed as transitional. Unit IIa and IIb are classified as Transitional soil changing to Silts and low I_r (rigidity index) clays with depth. Unit III falls on the border between Transitional soils and Silts and low I_r clays before the deeper Clay Unit IV is identified. The Robertson (1990) classification chart, see Figure 6, indicates that Unit I is a Silt mixture with some transition into Sand mixture and Sands. Using this chart, Unit IIa, IIb and III are all Clays (clay to silty clay) with some transition into the Silt mixtures. Unit IV also a Clay (clay to silty clay) plots on the far right of the figure.

The Schneider et al. (2008) classification chart in Figure 7 presents a slightly different classification for the soil units as Units IIa and IIb both fall in Silts and low I_r clays classification and do not cross into the Transitional soils area. The classification for Unit III is Silts and low I_r clays before the deeper Clays / Sensitive Clays. Overall this $Q_t - \Delta u_2 / \sigma'_{v0}$ chart from Schneider et al. (2008) shows a clear classification of Silts and low I_r clays. It is also notable that Unit IIa and IIb are grouped separately within this classification. Unit I is a distinctively different material and clearly falls in the transitional soils classification in contrast to Unit II.

6 ENGINEERING PROPERTIES

Two CAUC tests were performed on 72 mm specimens from Units IIa and IIb, from 5.3 m and 8.6 m depth, respectively. Both specimens were consolidated to a best estimate vertical effective stress σ'_{v0} using K_0 of 0.5. The change in $\Delta e/e_0$ during sample consolidation was less than 0.02 for both specimens. Sample quality is therefore qualified as very good to excellent for and OCR of 1 - 2 according to Lunne et al. (1997). However it is noted that this criteria was developed for marine clays and might not be applicable to intermediate soils. The normalised shear stress with strain behaviour showed a steady increase in shear stress for both samples. At 10% axial strain the samples had normalised shear stress in the region of $\tau/\sigma'_{v0} = 0.7 - 0.9$. The normalised pore pressure reached a peak in the region of $\Delta u/\sigma'_{v0} = 0.14$ before 1% strain and the test specimens dilated strongly. The stress paths showed a clear 'S' shaped response before dilation. The samples had clay contents of 11% and 17% determined by the falling drop method. The silt content was approximately 65% and I_p was less than 10% for both samples. At peak pore pressure the normalised shear stress is in the range of 0.4 - 0.45. The measured response from

the tube samples is thought to be representative of good quality silt samples considering the corresponding index data.

7 DISCUSSION

Initially the silt deposit at the Halden Resesarch Site showed to be very homogenous. No layering was observed and the sediment proved to be structureless even with X-ray imaging. However, combining the data obtained from *in situ* testing, classification testing and the Multi Sensor Core Logger one can observe two distinct silt units. Units II and III differ slightly in terms of water content, total unit weight and magnetic susceptibility. This correlates also with an increase in corrected cone penetration resistance from 12 m. Reasons for this gradual change are not fully understood, but one possibility is that such subtle changes are linked to variation in organic matter as observed in both units. This interpretation is corroborated by other studies of geotechnical properties of marine sediments which showed to be altered to varying degrees by subtle changes in organic content (e.g. Keller 1982, Booth & Dahl 1986). Organic matter absorbs water and causes clay-sized particles to aggregate forming an open fabric. This causes an increase in water content and plasticity, and a decrease in the total unit weight. Since the mineralogical contents of both Units II and III are almost identical, the changes in magnetic susceptibility and gamma density obtained from MSCL-S could be linked to the observed patterns of organic matter and water contents (c.f. St-Onge et al. 2007).

The variations between the different SBT charts highlight the importance of cross checking CPTU interpretation of soil classification or behaviour type with index data. Falling drop grain size data for Unit IIa and IIb show average clay content of 13.4% and Unit III lower at 9% clay content. There is evidence that clay contents may be lower based on hydrometer results. For example, in Units IIa and IIb the clay content is in the range of 7.8% and 3% to 7% in Unit III. Clay contents at the lower bounds are questionable as Atterberg limits were measured on the material in Unit III. The plasticity index data for Unit IIa and IIb agrees well with the clustered results in the soil classification charts as Unit IIa is just on and below the A-line and has a higher I_p while Unit IIb plots on the A-line and has a lower I_p . Unit I, a transitional soil plots just below the A-line and has a low I_p which agrees well with the classification charts for both Robertson (1990) and Schneider et al. (2008). The soil classification based on CPTU results in Units IIa and IIb plot in a similar region of the Q- B_q chart (Schneider et al. 2008) as CPTU data from a silt site, Halsen, in Northern Norway tested by Sandven (2003).

A very limited program of advanced tests are carried out on the Halden silt. However, the normalised shear stress τ_f/σ_{v0}' interpreted at peak pore pressure in the CAUC tests are in the range of 0.4 to 0.45. This is slightly below the ratios presented by Brandon et al. (2006) for Yazoo and LMVD silt, but within the range reported by Long (2007) for the estuarine Sligo silt.

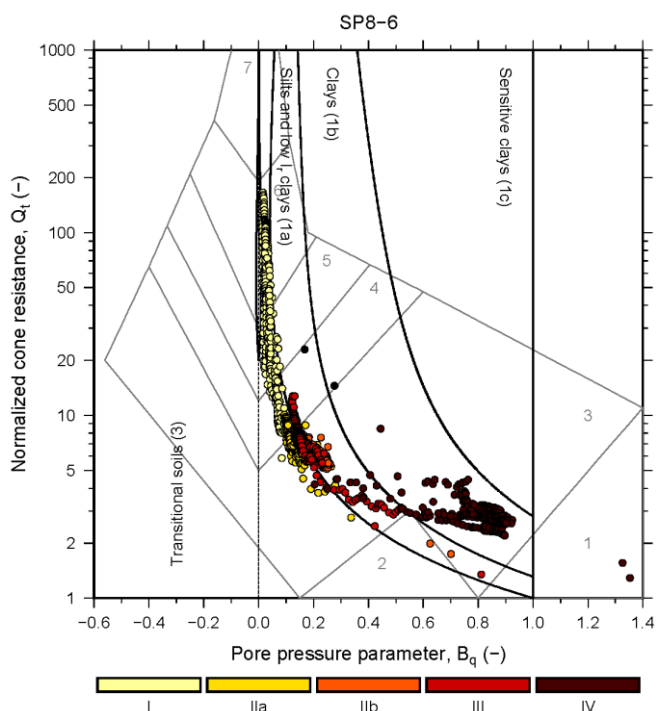


Figure 6. Robertson (1990) soil behaviour type chart for SP8-CPT-6.

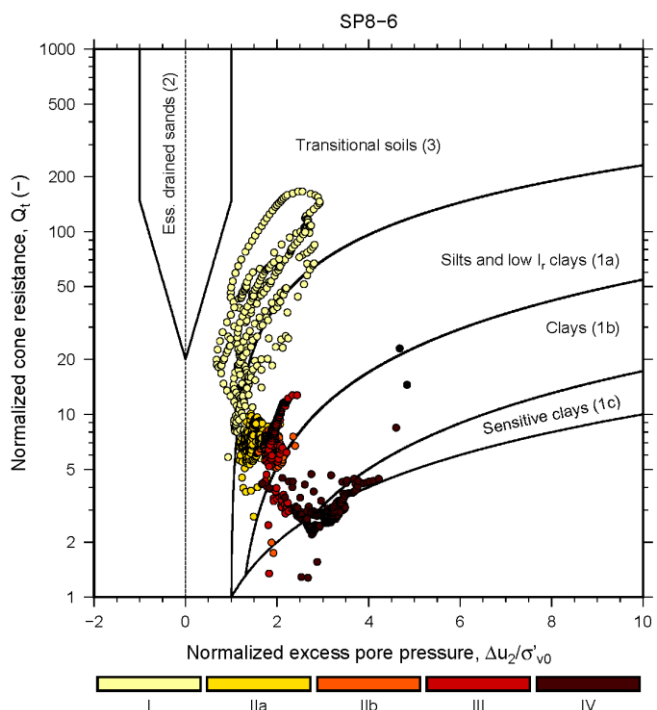


Figure 7. Schneider et al. (2008) soil behaviour type chart for SP8-CPT-6.

This study has detailed some characteristics and engineering properties of the Halden silt, a 11 m thick deposit of fjord marine silt in south-eastern Norway. NGI recently established a research site on this deposit to accommodate some of the challenges related to intermediate soils. A variety of *in situ* and laboratory tests have been performed to investigate its properties. Some preliminary conclusions are:

(i) The silt is considered normally consolidated and is of low plasticity, with a clay content between 8% – 18%.

(ii) Similar mineralogical content of the silt layers, Units II and III, is found. The soil consists mainly of quartz, K-feldspar and plagioclase, with 7% - 8% muscovite/illite.

(iii) Corrected cone resistance from CPTU in Unit II and III shows a 1 MPa to 2 MPa response, while pore pressures are positive and steadily increasing with depth down to the clay layer.

(iv) Patterns of water content, unit weight, magnetic susceptibility and cone penetration resistance could be attributed to subtle changes in organic content. Reasons for these gradual change are not fully understood and will need further studies.

(iv) Various SBT charts classify the soils as transitional soils or silts to low I_r clays. The Schneider et al. (2008) $Q_t - \Delta u_2 / \sigma_{v0}'$ chart shows a clear classification of Unit II-IV as Silts and low I_r clays, and separates Unit IIa and IIb from each other.

(v) The variation between the different SBT charts highlights the importance of cross checking CPTU interpretation of soil classification or behaviour type with laboratory index data.

(vi) CAUC tests on 72 mm silt specimens from Unit II indicate a normalised shear stress at failure the region of $\tau_f' / \sigma_{v0}' = 0.4 - 0.9$, depending on the failure criteria selected.

The results contribute to the developing global knowledge of properties and behaviour characteristics of intermediate soils. Further studies are planned at this site to better understand factors controlling the mechanical response of intermediate soils.

9 ACKNOWLEDGEMENT

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