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Geotechnical characterization of the Tiller-Flotten quick clay site in Norway

Caractérisation géotechnique du site d'argile sensible de Tiller-Flotten en Norvège

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ABSTRACT: The Tiller-Flotten test site consist in a more than 50 m thick and uniform marine clay deposit. The top 8 m of the deposit shows a low sensitivity, while sensitivity increases up to approximately 200 from 8 to 20 m below the ground surface. A wide variety of in situ testing and laboratory data have been acquired to investigation the geotechnical, geological and geophysical properties of the material. The clay shows a medium plasticity (Ip≈ 15) and a liquidity index (I_L) up to 1.5. It shows some overconsolidation (OCR≈1.5-3.0) linked to the glacial history of the area. Its strength and stiffness properties show good agreement with some well-known correlations for sensitive clays. Anisotropy in undrained shear strength is also similar to other sensitive clays of Norway. It is hoped that the next years will see an increase use of this testing site at Tiller/Flotten. The site can be use as a research tool, as training and teaching facilities and as ground for development of new soil models, testing of new investigation methods and further advance the state-of-the-art in sensitive clay material.

RÉSUMÉ: Le site de Tiller-Flotten en Norvège consiste en un dépôt d'argile marine, uniforme, d'une épaisseur de 50 m. Les 8 premiers mètres du dépôts présentent une faible sensibilité, tandis que la sensibilité augmente à plus de 200 entre 8 et 20 m sous le terrain. Une grande variété de données in situ et de laboratoire ont été acquises pour étudier les propriétés géotechniques, géologiques et géophysiques du matériau. L'argile présente une plasticité moyenne (Ip≈15) et un indice de liquidité (IL) allant jusqu'à 1,5. Le matériau montre une surconsolidation (OCR≈1,5-3.0) liée à l'histoire glaciaire de la région. Ses propriétés de résistance et de rigidité sont en accord avec certaines corrélations bien connues pour les argiles sensibles. L'anisotropie de la résistance au cisaillement non drainé est également similaire à celle des autres argiles sensibles de la Norvège. Ce site peut servir d'outil de recherche, d'enseignement, et permettra de développer de nouveaux modèles de sol, de calibrer nos méthodes d'investigation et de faire progresser les techniques de pointe en matière d'argile sensible.

Keywords: Sensitive clay; site characterisation; in situ testing; benchmark test site.

1 INTRODUCTION

Deposits of sensitive marine clay are found over large areas of Norway, Sweden, Finland and Canada. Such deposits are extremely challenging to deal with for geotechnical engineers. In particular, sensitive marine clay deposits are frequently associated with landslides triggered by natural or man-made events, posing a constant threat to society.

The challenges for geotechnical engineers working with sensitive clay material are often associated with sampling of undisturbed material and interpretation of in situ and laboratory data. There is a need to provide guidance to practicing engineers working in such problematic soils. 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 National testing facility on a sensitive marine clay deposit within the Norwegian GeoTest Site project (NGTS) (L'Heureux et al. 2017).

The objective of this paper is to present preliminary results from several field campains and laboratory work done on the sensitive marine clay at the newly established Tiller-Flotten research site outside Trondheim. The results presented will form a useful reference to engineers working on such soils.

2 LOCATION AND SETTINGS

The Tiller-Flotten research site is situated approximately 20 km south of Trondheim in mid Norway. The site is primarily used for agricultural purposes and the area available for geotechnical studies is about 150 m by 300 m. Deposits at the site consist of fjord-marine, marine and glaciomarine sediments that emerged from the sea following a fall in relative sea-level around the Trondheimsfjord region during the last c. 11,000 years.

The research site is at an elevation of 125 masl and drains towards the Nidelava river located at an elevation of 72 masl approximately 700 m to the southeast (Figure 1).

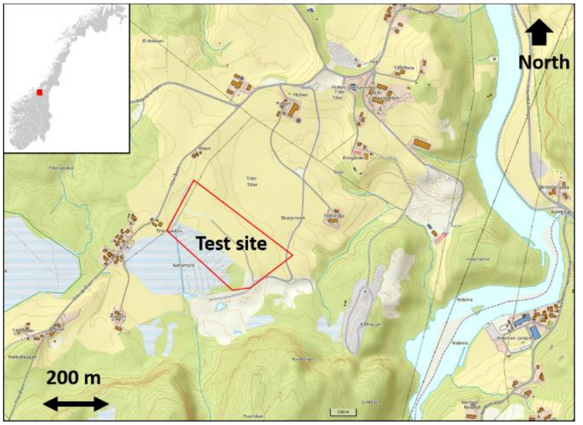

Figure 1. Location of Tiller-Flotten Research site.

3 FIELD AND LABORATORY METHODS

3.1 Field tests

Several investigation methods have been used to characterize the natural clay 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), Multi Spectral Analysis of Surface Waves (MASW), Total Pressure Soundings (TPS), Cone Penetration Tests with pore pressure measurements (CPTU), Cone Penetration Tests with resistivity sounding (RCPTU), Seismic Cone Penetration Testing (SCPTU), Seismic Dilatometer Tests (SDMT), piezometer tests, and collections of undisturbed samples. The undisturbed samples were collected using 54 mm piston samplers, a mini-block sampler (Emdal et al. 2016) and with the traditional Sherbrooke sampler.

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. Testing was also performed at the NTNU laboratories in Trondheim. In sum laboratory tests include; (i) Grain size distribution analyses by wet sieving (NSF, 1990), falling drop method (Moum, 1965) and hydrometer method (BSI, 1990); (ii) a range of index tests; (iii) CAUC and CAUE triaxial tests; (iv) constant rate of strain oedometer tests (CRS); (v) direct simple shear tests (DSS); (vi) 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.

Unconfined measurements of shear wave velocity ($V_{s\text{-}0}$) were collected in the laboratory using the bender element device described by Landon et al. (2007). For this, samples were carefully trimmed from block samples size to a cube about 70x70x70 mm size due to restriction in the equipment size. Shear wave velocity was also measured using bender elements in the triaxial cell after consolidation at in situ stresses ($V_{s\ \text{confined}}$). Furthermore, shear-wave velocity data were acquired in the field using a seismic dilatometer ($V_{s\text{-in situ}}$).

4 SOIL CHARACTERIZATION

4.1 Stratigraphy and structure

The stratigraphy at the site is divided into three main units based on laboratory and in situ testing results (Figure 2). The top unit (unit I) is c. 2 m thick and consists mostly of dessicated and weathered clay. Unit II is divided in two parts (i.e. Unit IIA and IIB). Both sub-units show similar clay content and structure, but differ in terms of soil sensitivity. The clay of unit IIA is found from 2 to 7.5 m below the surface and shows a low to medium sensitivity. From 7.5 m below the ground surface the clay shows extreme sensitivity, often above 100. Below the depth of 19.5 m the clay of unit III contains several thin sandy layers. The change from Unit II to Unit III could mark the boundary between marine and glaciomarine conditions that occured in the study area in the younger Dryas period (c. 10,500 yrs before present). However, radiocarbon dating are not available at present to justify this.

X-ray analyses show that the clay of Unit II is laminated with darker and lighter intervals. This layering is also observed on the MSCL results, as exemplified in Figure 3. The darker layers correlated to peaks in gamma density and magnetic susceptibilty on the MSCL logs, which could reflect the coarser nature of these layers.

4.2 Index properties

The total unit weight (γ_t), clay content, water content and Atterberg limits of the clay at Tiller-Flotten are presented in Figure 2. The total unit weight of the clay is generally around 18 kN/m^3 while the clay content varies between 50-70%. The water content at the top of Unit IIB (i.e. sensitive clay) is around 45% and slightly decreases with depth towards a value of 40% at 20 m. The water content is above the liquid limit w_L throughout unit IIB while the plasticity index (I_p) varies between 8-18. On the plasticity chart the sensitive clay of unit IIB plots in the CL zone of low plasticity (Figure 4).

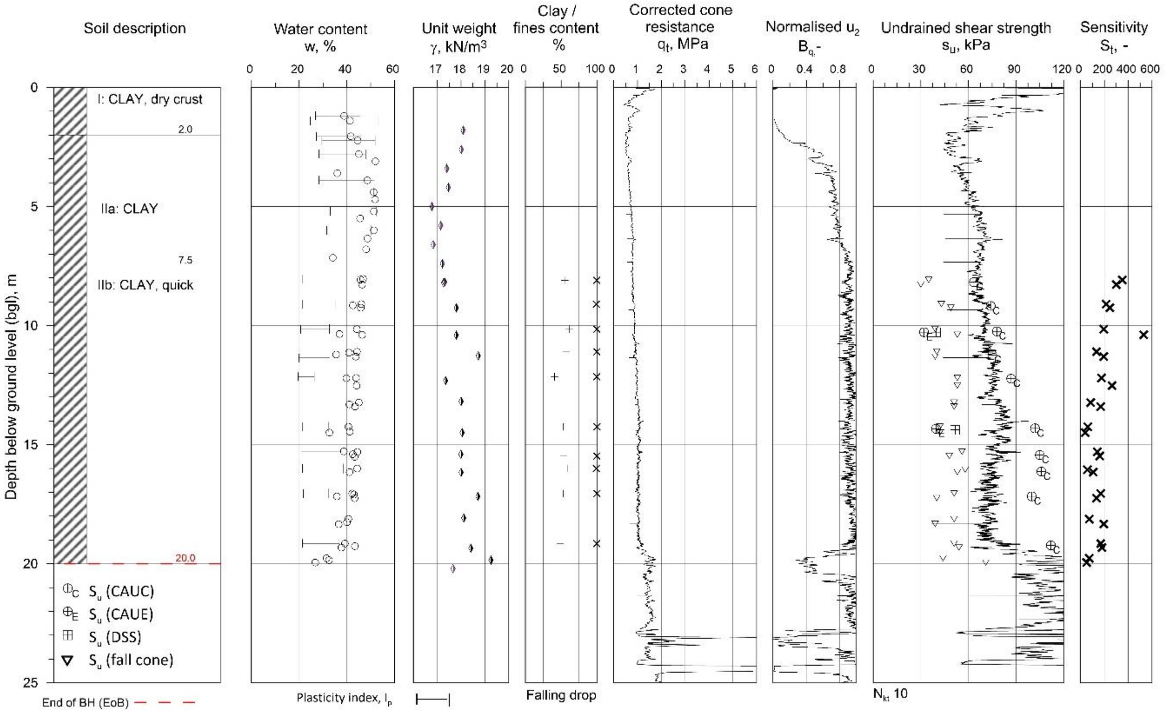

Figure 2. Basic soil profile and stratigraphy at the Tiller-Flotten site from laboratory tests on block samples and cone penetration testing (CPTU).

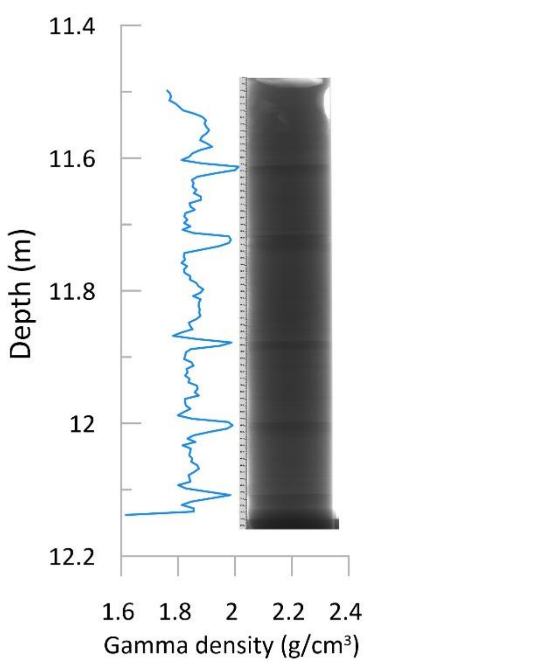

Figure 3. Example of gamma density and X-ray section at depth 11.4 – 12.2 m.

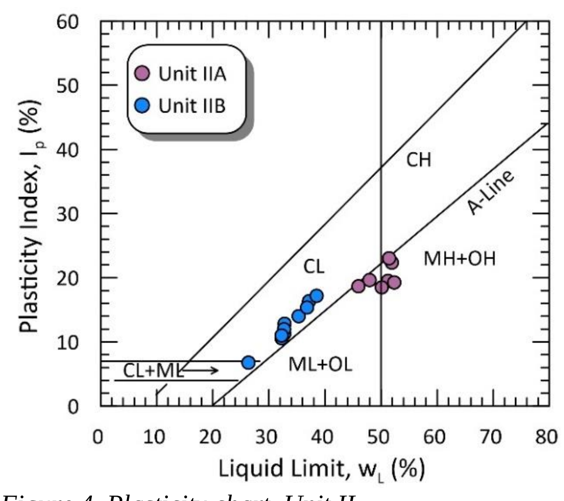

Figure 4. Plasticity chart, Unit II.

5 CONE PENETRATION TESTING

With the evaluation of CPTU soundings in clays, the initial concern is in the proper identification of fine-grained soils which are sensitive. The evaluation of soil type is usually done via empirical charts that assign a soil behavioral type (SBT), such as those presented by e.g. Robertson (1990) and Schneider et al. (2012).

Despite the widespread use of these SBT charts, the proper identification of sensitive and structured clays is not always so successful. Figure 5 presents the traditional soil behaviour type chart (SBT) from Robertson (1990). This system is based on the normalized cone resistance parameter Qt and the normalized friction ratio Fr, and on Qt and the pore pressure parameter Bq. Unit I is classified as a transitional silt and sand mixture on Figure 5. Units IIA, IIB and III are classified as clay to silty clay. Only a few points fall in the sensitive fine grained zone. According to the SBTn charts, much of these data should fall into zone 1 (sensitive soils).

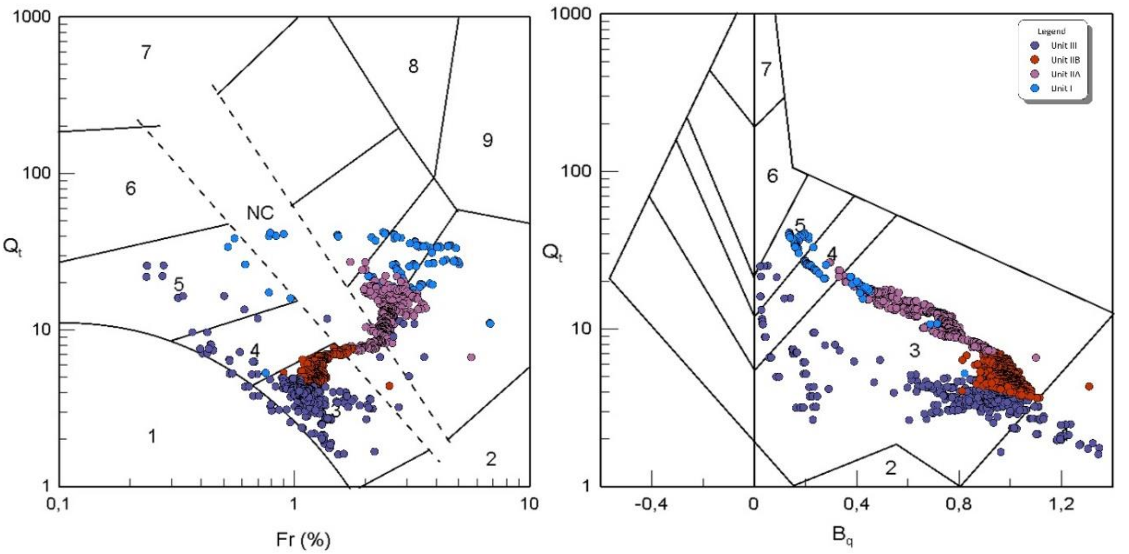

Figure 5. Robertson (1990) soil behaviour type chart for CPTU data at Tiller-Flotten (TILC01). 1- Sensitive fine grained, 2. Clay – organic soil, 3. Clay – clay to silty clay, 4. Silt mixture, 5. Sand mixtures, 7. Dense sands, 8. Stiff sand to clayey sand (OC or cemented), 9. Stiff fine grained (OC or cemented).

6 GEOPHYSICAL DATA

A total of six Electrical Resistivity Tomography (ERT) profiles were performed in November 2017 at the Tiller-Flotten site. An example of ERT profile acquisition results is presented in Figure 6. The final RMS (root mean square of the misfit between the data and the models) is 0.7%, which is considered good. The interpretation of the ERT profiles is based on the scheme proposed by Solberg et al. (2008) for Norwegian clays:

- Non-leached marine clay: 1-10 Ωm
- Leached, possibly quick clay: 10-80 Ωm
- Dry crust clay, slide deposits, coarser material like sand and gravel and bedrock: >80 Ωm

On all ERT profiles, the top 1-5 meters is marked by a resistive (ρ > 100 Ωm) dry crust layer. This top layer thickens towards the south at the site. The layer below the dry crust corresponds to unit IIA and shows resistivity values typical of marine clay (< 20 Ωm). This layer is very thin and not well resolved over the entire area. Below ~10m depth, resistivities typical of leached clay (20-100 Ωm) are observed in unit IIB. A very conductive layer (< 15 Ωm) is observed below 40 m depth. This layer corresponds to the clay of unit III.

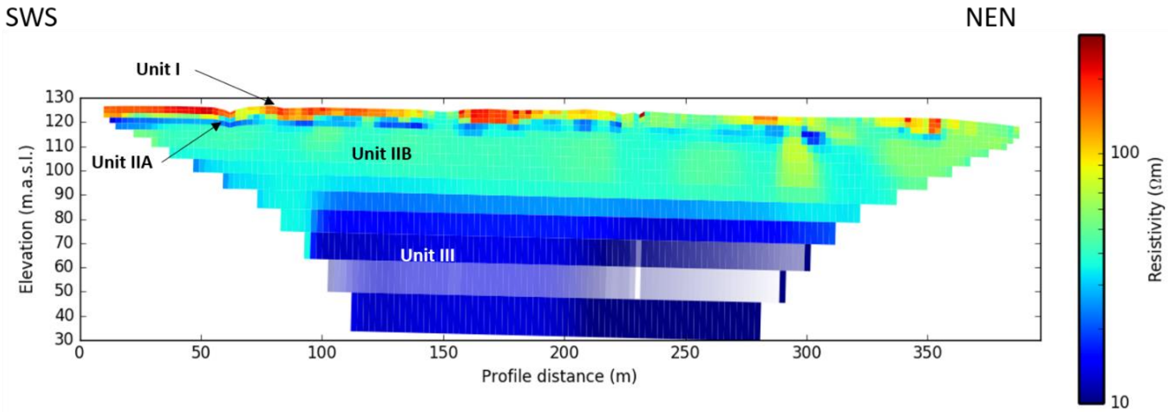

Figure 6.Result of ERT acquisition at Tiller-Flotten (profile 1).

7 ENGINEERING PROPERTIES

7.1 Preconsolidation and OCR

Yield stress, or preconsolidation stress, have been estimated from 1D CRS oedometer tests results (Figure 7). The results suggest that the preconsolidation stress is nearly twice the in situ vertical effective stress with an overconsolidation ratio (OCR) of 2.3 at a depth of 7 m and and OCR value of 1.7 at 19.5 m. The apparent overconsolidation of the clay is likely a result of the geological history in the area.

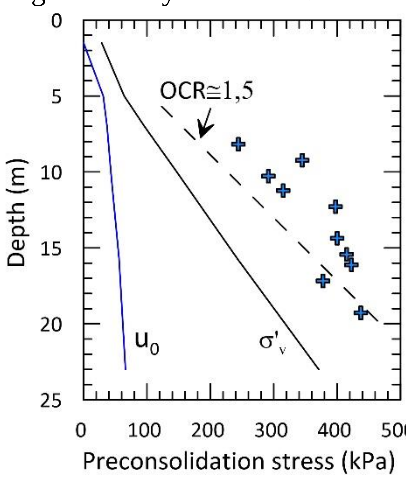

Figure 7. Yield stress or preconsolidation stress with depth interpreted using the Karlsrud and Hernandez-Martinez (2003) method.

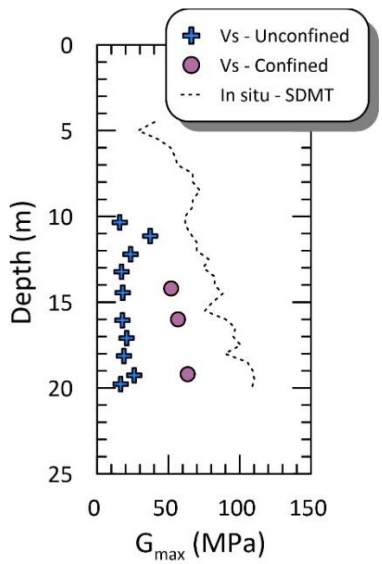

Figure 8. Small strain stiffness profile obtained from in situ measurement and laboratory measurement on unconfined and confined samples.

7.2 Small strain stiffness

Shear wave velocity (V_s) data was obtained in situ with the SDMT, and on samples using bender elements. The small strain stifness was determined according to the elastic theory and Eq. [1]:

$$G_{max} = \rho \cdot V_s^2 \quad (1)$$

where G_{max} is the small strain stiffness (in Pa), V_s

is the shear wave velocity (in m/s), and ρ is the density (in kg/m3). Figure 8 presents the results of G_{max} with depth. As seen on this figure, the in situ stiffness is higher than that measured on the samples. It can be seen that reconsolidation of the samples to the in situ stresses ($V_{s\text{-confined}}$) still gives G_{max} values 25-40 % lower than that measured in situ.

7.3 *Undrained shear strength*

Results from undrained shear strength testing (i.e. CAUC, CAUE, DSS and fall cone) on block samples in the laboratory are presented on Figure 2. In general the strength increases linearly with depth, but there is a small decrease in strength from 15-20 m. This is also observed on the strength interpreted from the CPTU data. One measure of the anisotropic nature of clay is determined by the anisotropic ratio:

$$K_1 = s_{u,CAUE}/s_{u,CAUC} \quad (2)$$

$$K_2 = s_{u,DSS}/s_{u,CAUC} \quad (3)$$

The anisotropic shear strength ratio are fairly constant in Unit IIB with K_1 ranging from 0.39 to 0.41 and $K_2 = 0.51$. These values are lower and higher than that recommended in NIFS (2014), respectively. However, the K_1 value is equivalent to that suggested by Ladd (1991) for lightly to normally consolidated clays and following a relationship of the form:

$$K_1 = 0.37 + 0.0072 I_p \quad (4)$$

Part of the strength anisotropy is expected to be linked to the layering observed in the clay at this site (Figure 3).

Typical remoulded shear strength (s_{ur}) data for the clay of Unit IIB is shown on Figure 9. Values less than 1 kPa are normally recorded. It is generally recognized that a relationship exists between remoulded shear strength and liquidity index. Leroueil et al. (1983) suggest that for the sensitive Champlain marine clays, the relationship which best fits the data is:

$$s_{ur} = 1/(I_L - 0.21)^2 \quad (5)$$

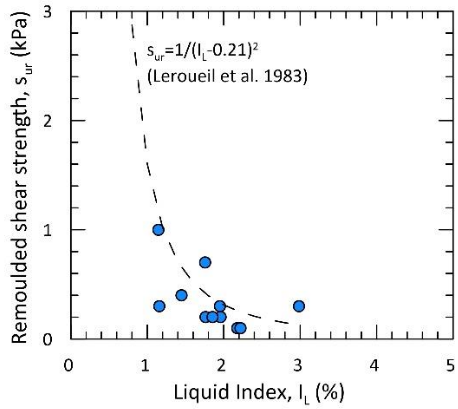

Figure 9. Typical undrained shear strength data as a function of the I_L for the clay of Unit IIB.

For Tiller-Flotten I_L is between 1 and 3 in unit IIB and the data is consistent with Leroueil et al. (1983) relationship (Figure 9).

7.4 *Sample quality*

It is well known that the effect of sample disturbance may considerably alter the determination of reliable soil parameters in soft and sensitive clays. To assess the quality of the samples collected at the research site, the methodology defined be Lunne et al. (2006) was used. The results reported in Figure 10 show that most samples fall in the category "very good to excellent", while the deeper samples fall in the category "good to fair".

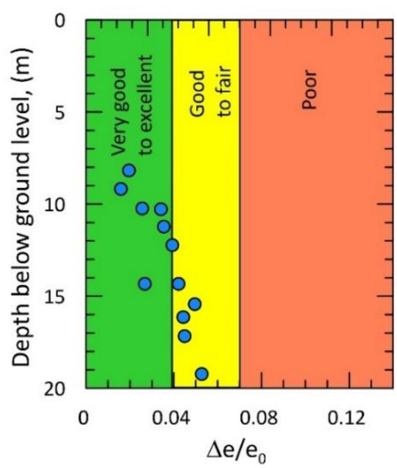

Figure 10. Sample quality assessment from triaxial test results based on the Lunne et al. (2006) criteria.

8 CONCLUDING REMARKS

This study has detailed some characteristics and engineering properties of the Tiller-Flotten clay, a thick deposit of marine clay in mid Norway. A wide variety of in situ devices and different laboratory tests have been used to investigate its properties. The clay is lightly overconsolidated, is of low plasticity and is “very sensitive”. Its properties show good agreement with some well known correlations. This research site is intended for the entire geotechnical profession, for both basic and applied geotechnical research and for education purposes. Some large scale testing is already being performed at the test site and it is hoped that the site will be used for many generation to come.

9 ACKNOWLEDGEMENTS

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